INFORMATION TO USERS

DISINTEGRATION OF Li^6 BY DEUTERONS

A thesis submitted to the Faculty of the
Rice Institute in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

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1. INTRODUCTION

The foremost problem in nuclear physics today
is the nature of the forces which act between nucleons.
One approach to this problem, suggested by the method
employed so successfully in the field of atomic spectroscopy,
is a careful study of the energy spectra of nuclei in search
of some regularity in the spacing of the levels. Accordingly,
in the past fifteen years a great deal of experimental work
has been devoted to the location of these energy levels.
Many levels have been found, about one hundred in the nuclei
of mass number less than twenty, but not yet enough to
reveal any significant patterns, and experiments to locate
still more of them are being carried out in many laboratories.

The most direct and accurate experimental method of
locating nuclear energy levels is the determination of the
excitation functions for various nuclear reactions. When
a target nucleus A collides with a bombarding nucleus B,
it is supposed that a compound nucleus C may be formed by
the interaction of A and B. The probability that such an
interaction will take place depends upon how nearly the
excitation energy of the compound nucleus thus formed coin-
cides with one of the natural energy levels of nucleus C.
The compound nucleus will lose its excess energy by the
emission of one or more particles or gamma rays, which can
be observed experimentally, and a high probability of inter-
action between A and B will result in the emission of a

large number of particles. The excitation function is a
measure of the number of particles emitted from a given
target per incident bombarding particle, expressed as a
function of the bombarding energy, and this function can
be determined by experiment. The bombarding energy for
which the excitation function has a relative maximum value
is therefore the bombarding energy for which the probability
of interaction between A and B is a maximum, which is the
bombarding energy which excites the nucleus C to one of
its natural energy levels. If this bombarding energy is
known, the excitation energy can be calculated from the
difference in the masses of the nuclei involved.

The nuclear spectra that can be analyzed in this
way are restricted in practice by the availability of suit-
able target nuclei from which the desired compound nucleus
can be formed by combination with the one of usual bombard-
ing particles (protons, deuterons, alpha particles, and
neutrons). In particular, the compound nuclei formed in
reactions with some of the less abundant isotopes have not
been studied extensively because of the difficulty in
observing particles emitted from one reaction in the presence
of like particles emitted from reactions involving the
other isotopic constituents of the target. It is for this
reason that the spectrum of Be^8 above 22 mev has not been
studied extensively. Be^8, excited to 22 mev, is formed by
the interaction of a deuteron with an Li^6 nucleus,

and the range of the spectrum above 22 mev that can be observed in this way simply depends on the available deuteron bombarding energy. However, normal lithium contains only 7.5% Li^6, and both Li^6 and Li^7 take part in similar reactions under deuteron bombardment. Targets of the separated Li^6 isotope are required for the most satisfactory study of the excitation functions for the $Li^6 + H^2$ reactions.

Oliphant, Shire, and Crowther[1] first prepared targets of the separated Li^6 isotope in 1934, using an apparatus similar to a mass spectrograph. With these targets they were able to identify the $Li^6(d,\alpha)\alpha$ and $Li^6(d,p)Li^7$ reactions. In 1937 Rumbaugh, Roberts, and Hafstad[15] separated small quantities of the Li^6 isotope with a similar electromagnetic separation process. In an extensive series of experiments, they identified all the known $Li^6 + H^2$ reactions, and determined the excitation function for most of the reactions for deuteron energies up to 1 mev.

In 1947 the Atomic Energy Commission made available for research purposes small quantities of the Li^6 isotope. The experiments reported in this thesis were undertaken with the purpose of (1) extending the excitation data on the $Li^6 + H^2$ reactions to the higher bombarding energies available with modern accelerating equipment, (2) determining the angular distribution of the particles emitted in the $Li^6 + H^2$ reactions.
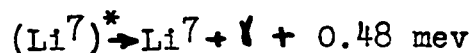
2. TARGETS

All of the targets used in these experiments were prepared from Li_2SO_4 containing lithium enriched to 95% Li^6. This compound was used because it is in this form that the Atomic Energy Commission furnishes the enriched isotope, and because the physical properties of Li_2SO_4 are well suited to the method of preparation described below. The presence of oxygen and sulfur in the target is not objectionable, since neither element is known to take part in deuteron induced reactions that cannot be easily distinguished from the $Li^6 + H^2$ reactions. The only undesirable element in the target is the 5% Li^7.

The powdered Li_2SO_4 was placed on a thin platinum strip which was then heated electrically in a vacuum chamber to about 1200° C. At this temperature the molten Li_2SO_4 evaporates readily but does not decompose. A thin film of the evaporated material was collected on the surface of a silver disc or foil placed 4 cm above the platinum strip, and the thickness of the layer was determined by weighing the disc before and after the evaporation. The pressure in the chamber was kept below 10^{-5} mm Hg during the evaporation process. At this pressure the mean free path of the molecules is several times the dimensions of the chamber, and all of the molecules are collected on the walls of the chamber or on the target disc and can be reclaimed by washing the walls down with distilled water.

3. PROTON EXCITATION FUNCTION

Two groups of protons of different range are observed when Li^6 is bombarded with deuterons. The two groups have been identified by Rumbaugh[15] with the reactions

(1) $Li^6 + H^2 \rightarrow (Be^8)^* \rightarrow Li^7 + H^1 + 5.0$ mev

(2) $Li^6 + H^2 \rightarrow (Be^8)^* \rightarrow (Li^7)^* + H^1 + 4.5$ mev

$(Li^7)^* \rightarrow Li^7 + \gamma + 0.48$ mev
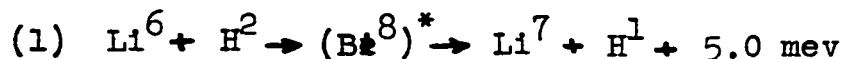
The range of the proton groups in center of mass coordinates at 1.0 mev bombarding energy is 34.2 cm for reaction (1), 29.6 cm for reaction (2). Since these are the only charged particles of this long range produced by deuteron bombardment of a Li_2SO_4 target, it is possible to count the two groups of protons together by introducing enough absorbing material between the target and the counter to stop all other charged particles of shorter range and let only these long range protons enter the counter. Then if more absorber is added to stop the shorter range group from reaction (2), the long range group from reaction (1) can be counted alone. The difference in the counting rate for two different amounts of absorber is then the counting rate for the short group alone. The difficulty with this procedure is that due to straggling the proton ranges are spread out over a few centimeters, and since the difference in the mean ranges of the two groups is only about 4.5, the two groups will overlap and only a partial resolution of the two groups will be possible.

There are two principal causes for this strag[gling]

First, the so-called range straggling which is due to [the] fact that the loss of energy by a charged particle is [a] statistical process, involving a large number of colli[sions] and leads to a Gaussian distribution of the ranges for [an] initially monoenergetic group of particles. In air th[e] straggling amounts to about a 6 mm difference between [the] mean range and the extrapolated range for a group of [protons] with 30 cm mean range, and the straggling becomes grea[ter] in absorbing media of greater stopping power. Alumin[um] absorbing foils and windows were used whenever possib[le] in the experimental apparatus to minimize this stragg[ling] since aluminum has a relatively low stopping power. [Since] the target thickness introduces a spread in the range [of] each group which is proportional to the target thickn[ess] This was kept to a minimum by using the thinnest targe[t] consistent with a reasonable counting rate.

The separation of the two groups is shown in [the] numbers-range curve of Fig (1), which shows the proto[n] counting rate as a function of the extra absorbing fo[il] protons together is well defined by the flat portion [of] the curve to the left. The step in the curve is not [?] flat, which indicates that the two groups overlap sli[ghtly] but the counting rate at that part of the step with m[?]
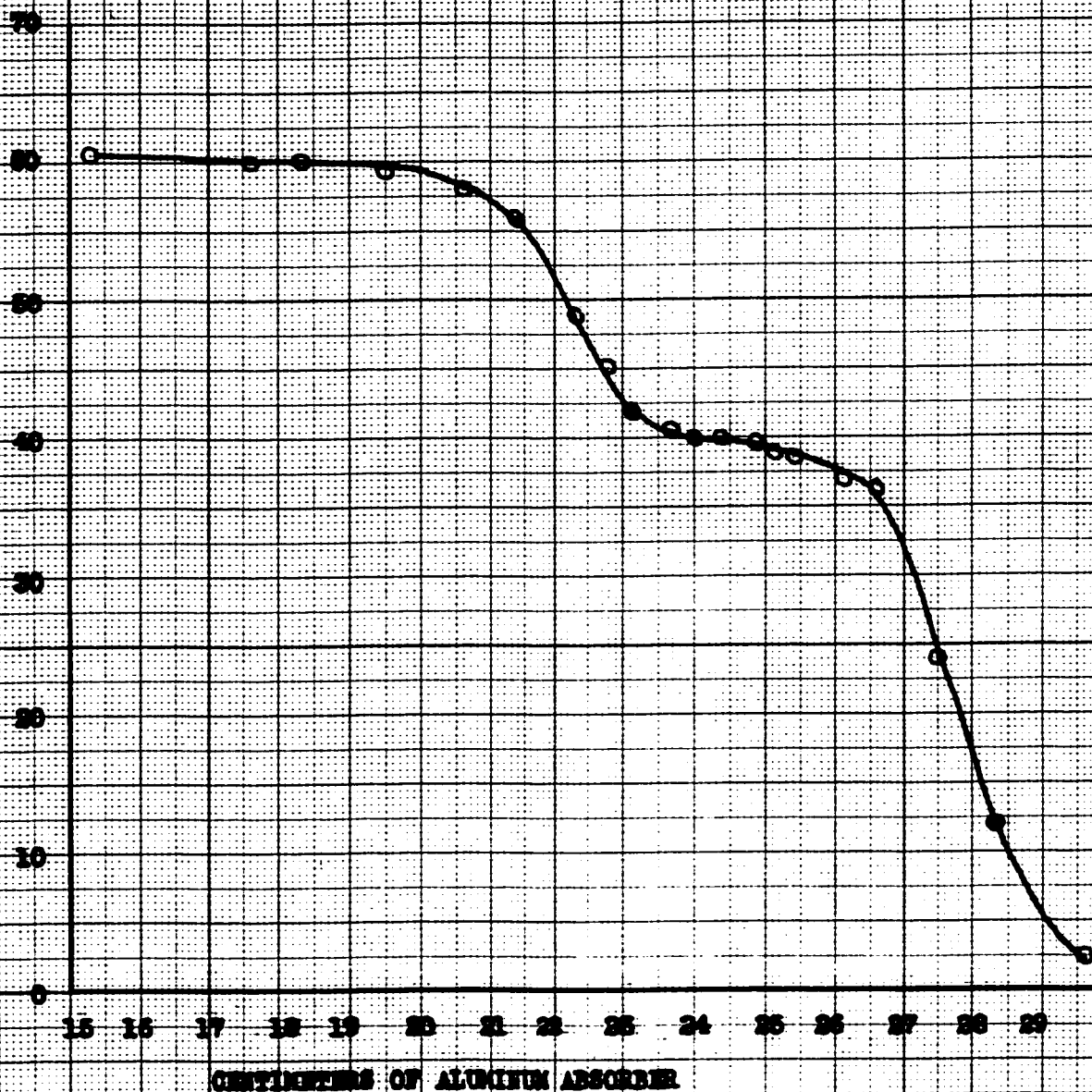
FIG. 1. RANGE-ENERGY CURVE SHOWING THE RESOLUTION OF THE TWO
PROTON GROUPS.

slope should be a good approximation to the counting rate
for the long group alone. Because the two groups overlap
in range, the excitation functions for the individual groups
can be determined only approximately by this method, but
the accuracy should be sufficient to reveal any considerable
structure in the excitation curve, and the simplicity and
speed of this method recommend its use for a first survey
of the excitation curve.

The experimental arrangement used in taking the
proton excitation curve and angular distribution data is
shown in Fig (2). The excitation curve was taken with the
counter placed in line with the beam and the target surface
normal to the beam. The protons must then pass through the
target backing to reach the counter. The target is a thin
film of Li_2SO_4, 127 microgm/cm^2 thick, evaporated on to
silver foil, 14.4 mg/in^2 thick. The silver foil is of the
minimum thickness that will completely stop the deuterons.
Silver, because of its relatively high stopping power,
increases the straggling of the protons, but it was not
possible to use aluminum target backing since deuteron
bombardment of aluminum produces several long range groups
of protons. The ports in the scattering chamber are covered
with aluminum windows, 37 mg/in^2 thick, which bulge in
slightly under the atmospheric pressure difference across
them and introduce further straggling, since the windows
are then thicker toward the sides than in the middle.

The counter used in this experiment is also shown in Fig (2). It is a simple proportional counter constructed from a brass cylinder (5/8" I.D.) with a 5 mil tungsten central wire. A round port (5 mm diam.) in the side of the counter is covered with a thin aluminum window and admits the protons into the counter. The counter was placed with its window 136 mm from the target, and care was taken to see that the counter window could see the entire area of the target covered by the deuteron beam. Attached to the counter is a frame which will support an absorbing foil in place before the counter window. A set of graded aluminum absorbing foils was prepared, varying in thickness from 0.46 cm to 32.5 cm of air. By using various combinations of these foils, the effective added absorber in the proton path could be varied from 0.46 to 50 cm, in steps of approximately 3 mm.

The counter was filled with commercial argon at 6" Hg pressure, and the voltage on the counter (1100v) was selected to give satisfactory gas amplification at this pressure. The voltage pulses from the counter were amplified in a linear amplifier (Atomic Inst. Co., Model 204-A) with a rise time of 0.8 microseconds, and the amplifier output was fed into a discriminator (Atomic Inst. Co., Model 101-A). The discriminator bias was set at the lowest value that would exclude counts from gamma rays, so that all the protons that entered the counter would be

ADJUSTABLE
SYLPHON BELLOWS
FOR ALLIGNMENT

BEAM FROM
MAGNETIC
ANALYZER

LUCITE
INSULATOR

0.5 C'M.
APERTURE

ROTATING 3/8"
BRASS PLATE

CYLINDER:
I.D. = 7"
O.D. = 7 1/4"
HEIGHT = 3 1/2"

TARGET AND SUPPORT ON BALL BEARING
WITH MAGNET AND POINTER FOR
ROTATION FROM OUTSIDE.

ALUMINUM FOILS
OVER 5/8" HOLES

ANGLE
GRADUATIONS

PROTON
COUNTER

PREAMPLIFIER

0.5
CM. APERTURE

ROTATING TEXOLITE COUNTER SUPPORT
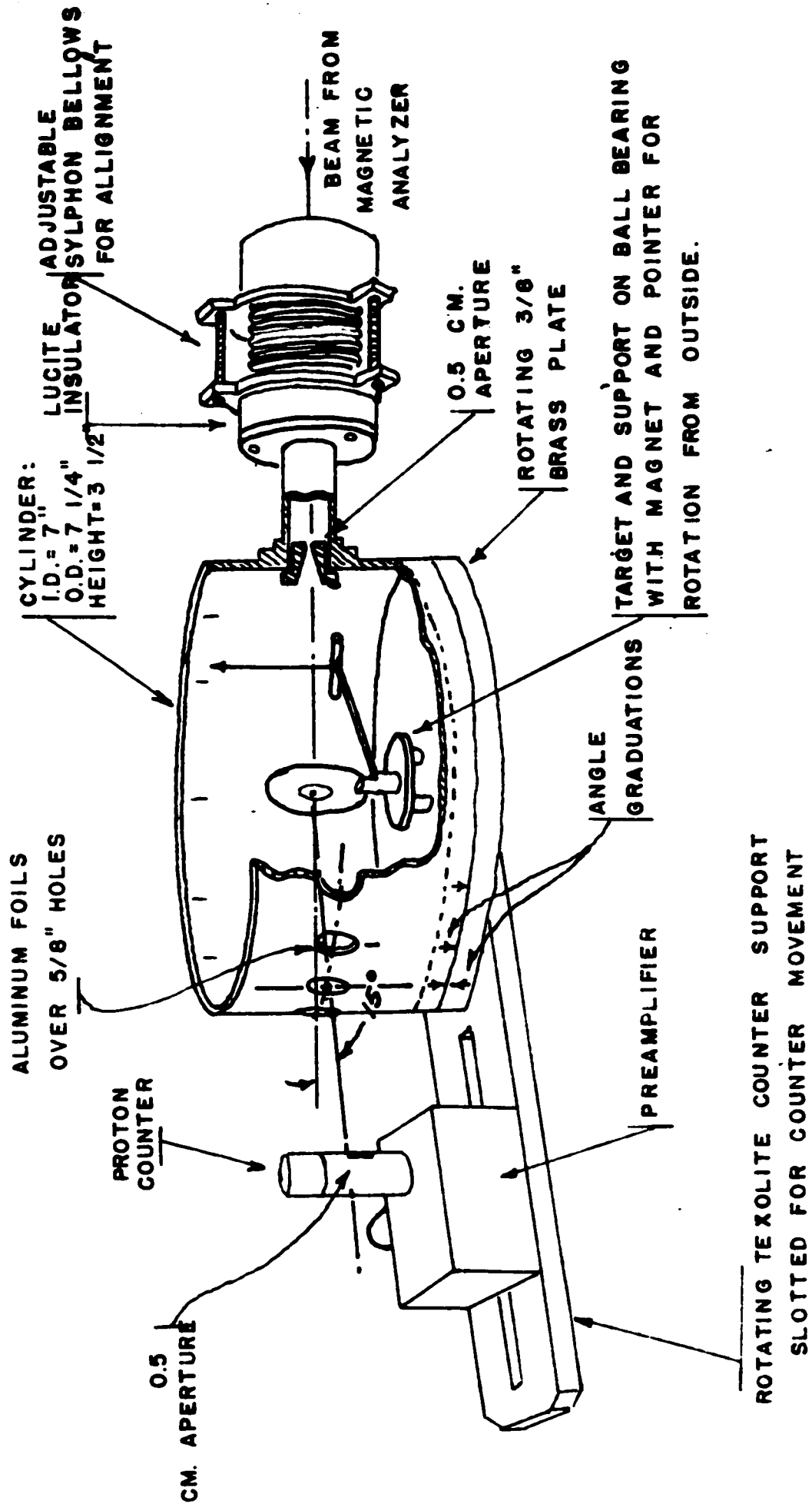SLOTTED FOR COUNTER MOVEMENT

FIG. 2

counted. The discriminator output was scaled down by a factor of 64 and recorded on a register.

A homogeneous beam of deuterons was obtained with the Rice Institute pressure Van de Graaff ion accelerator, which has been described elsewhere[17]. The deuteron energy was determined by deflecting the beam through 90° in the field of a large electromagnet which had been previously calibrated to give the deuteron energy directly in terms of the magnet current. The energy resolution is approximately $\pm$ 10 kev.

At each bombarding energy the amount of absorber in the proton path was adjusted for operation on the flattest region of the numbers-range curve step, to count the long group alone. Then 8 cm air equivalent of absorber was removed and the counting rate for the two groups together measured. The approximate amount of absorber necessary for counting the long group alone was calculated from the Q value of the reaction, the deuteron bombarding energy, and the known range-energy relationship for protons, but at each bombarding energy the counting rate for the long group was measured with at least two different amounts of absorber, differing by a few millimeters, to be sure that the numbers range curve was approximately flat. A count of at least 1280 protons was taken to determine the counting rate at each of these two positions on the numbers range curve. The results obtained by this procedure are plotted as

circles in Fig (3), which shows the proton counting rate
in arbitrary units plotted as a function of the deuteron
bombarding energy.

In the course of taking the proton angular distri-
bution data a much thinner target was prepared on a nickel
foil backing. With this target the resolution of the two
groups is considerably better. Numbers-range curves taken
with this target showed a slightly different ratio of the
intensity of the two groups at very low deuteron energies.
It is believed that the results of the measurements with
this thin target, plotted as crosses in Fig (3), are the
more reliable, and the solid curve has been drawn through
these crossed points.

The curves show no indication of any significant
structure. These results are in agreement with Rumbaugh's
measurements of the ratio of the intensities of the two
groups at several bombarding energies below 900 kev. A
discussion of these proton excitation curves is included
in the section on the $Li^6(d, \alpha)\alpha$ reaction.

4. PROTON ANGULAR DISTRIBUTION

The experimental arrangement used in measuring
the proton angular distributions is shown in Fig (2).
The counter and associated electronic equipment have been
described in the section on the proton excitation data.
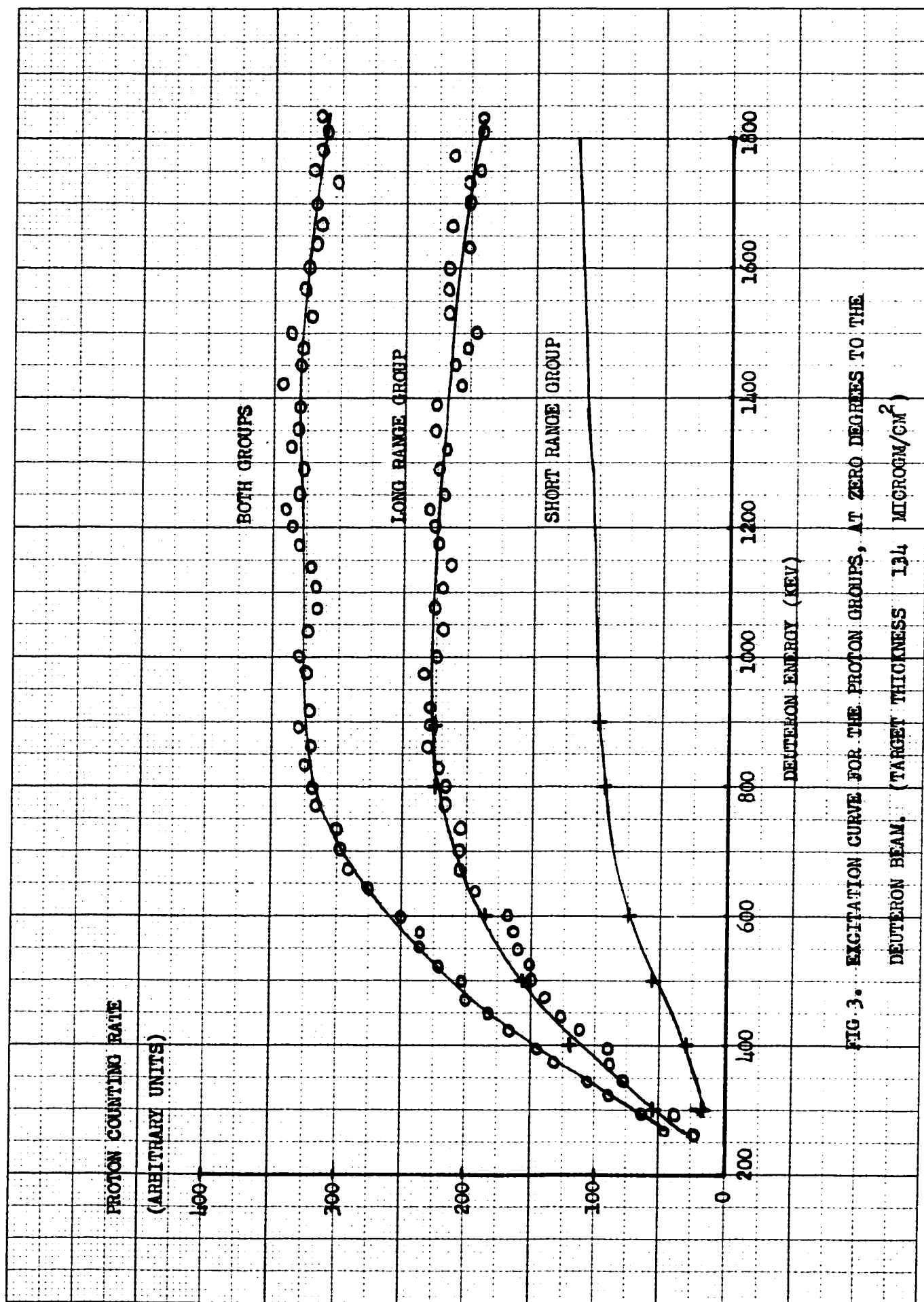As shown in the diagram, the counter is fastened by means

FIG. 3. EXCITATION CURVE FOR THE PROTON GROUPS, AT ZERO DEGREES TO THE
DEUTERON BEAM. (TARGET THICKNESS 134 MICROGM/CM^2)

of a Textolite arm to a heavy brass disc on the bottom of
the scattering chamber. A circular flange on this disc
fits in a groove on the bottom of the chamber, and the
disc is pivoted at its center so that the counter can be
moved along the arc of a circle to receive protons through
any of the windows in the chamber. On the rim of the brass
disc there is a fiduciary mark in line with the center of
the counter window, and by setting this mark on correspond-
ing lines on the sides of the chamber which mark the center
of the windows, very accurate location of the counter with
respect to the windows is assured. The ports in the chamber
(5/8" in diam.) are spaced at 15° intervals between -30°
and 150° (measuring the angle counter clockwise from the
beam, looking down from the top). The target holder, in
the center of the chamber, is mounted on ball bearings,
and by means of an iron arm that extends to within a few
millimeters of the chamber wall the target can be rotated
about a vertical axis with a small magnet outside the scatter-
ing chamber. A pointer at the end of this iron arm extends
up to the top of the chamber and moves over an angle scale
inscribed on the inner wall of the chamber. The lid of
the chamber is transparent Lucite, so that the angle setting
of the target can be read on this scale. The copper screen
supported just under the lid is electrically connected to
the chamber walls and serves to prevent electrical charges
from accumulating on the Lucite. The target holder is

electrically insulated from the chamber so that the
deuteron beam current striking the target can be measured
with a current integrator outside the chamber, the
electrical leads are taken out through the lid. Batteries
outside the chamber maintain a potential difference (135v)
between the target and the surrounding conductors to
suppress secondary electron emission from the target. To
observe the protons emitted at 90° to the beam, it was neces-
sary to turn the target at an angle; in this experiment the
45° target position was chosen. With the deuteron beam
striking the target at an angle, and the protons passing
through the target at an angle, it was found that the strag-
gling of the groups was increased, probably due to uneveness
in the target backing foil which would be more noticable
at this angle than with the target normal to the beam. To
reduce this straggling to a tolerable amount, a very thin
target was used (44 microgm/cm^2) and it was mounted on very
thin nickel foil (13.9 mg/cm^2), since the range straggling
in nickel should be less than in silver. This nickel is
not thick enough to stop deuterons of more than about 1.6
mev energy, even when turned at 45° to the beam, so that
angular distribution measurements are confined to deuteron
energies below this value.

The following procedure was adopted for observing
the angular distributions. At each angle 0°- 150° a
numbers-range curve was taken to determine as accurately

as possible the ratio of the two groups at each angle. During these measurements the target could be set at any convenient angle, since only the ratio of the counting rates was being measured. Then with the target set at 135° to the beam, the counting rate for the two groups together was measured over the 0° - 90° angles, taking a count of at least 2560 protons at each angle. Then the counter was turned to the 45° position and the counting rate measured from 90° to 150°. It was found that with the counter at the 90° position, the counting rate for the two target positions differed by about 10%, even though the target made the same angle with the beam in both positions, so that the two sets of data over the forward and backward angles did not fit together at 90°. To fit the data together properly, the counting rate at 0° was also measured with the target in the 45° position. Then the 0° - 90° data was multiplied by the proper factor to make it fit the 0°, 90° - 150° data best at both ends.

In this way the angular distribution of the two groups was determined, and knowing the ratio of the two groups at each angle, the angular distributions for each group alone could be calculated. These measurements give the distribution in laboratory coordinates, from which the distribution in center of mass coordinates can be calculated from the deuteron bombarding energy and the Q value for the reaction. The angular distributions in center of mass angle

for four deuteron bombarding energies are plotted in Fig (4). The proton counting rate is in arbitrary units, but is the same for each curve.

The experimental distributions plotted in Fig (4) have been expanded in terms of the first seven Legendre polynomials. If $Y(\cos\theta)$ is the experimental distribution function, the coefficients in the expansion of $Y(\cos\theta)$ are given by

$$A_l = \frac{2l+1}{2} \int_{-1}^{+1} Y(\cos\theta)\, P_l(\cos\theta)\, \mathcal{L}(\cos\theta)$$

The integration has been carried out by means of Simpson's rule, for a second degree curve through the experimental points, with an interval $\cos\theta = 0.05$ between adjacent points to which the second degree curve is fitted. This requires that the function $Y(\cos\theta)$ be known at 41 equally spaced intervals between $\cos\theta = -1$ and $\cos\theta = +1$; these values were taken from the smooth curve drawn through the ten experimental points and extended 'by eye' from $150°$ to $180°$ as is shown by the dotted section of the curves in Fig (4). The values of the coefficients obtained in this way for both of the proton groups together, and for the long group alone, are listed in Table I. The coefficients of the short group were then obtained by subtracting the coefficient for the long group from the corresponding coefficient for the two groups together. The functions defined by these coefficients fit the experimental curves to within less than experimental error. For example, the maximum deviation between $Y(\cos\theta, 1.4\text{ mev, both groups})$ and the function defined by the calculated coefficients is less than 3%.
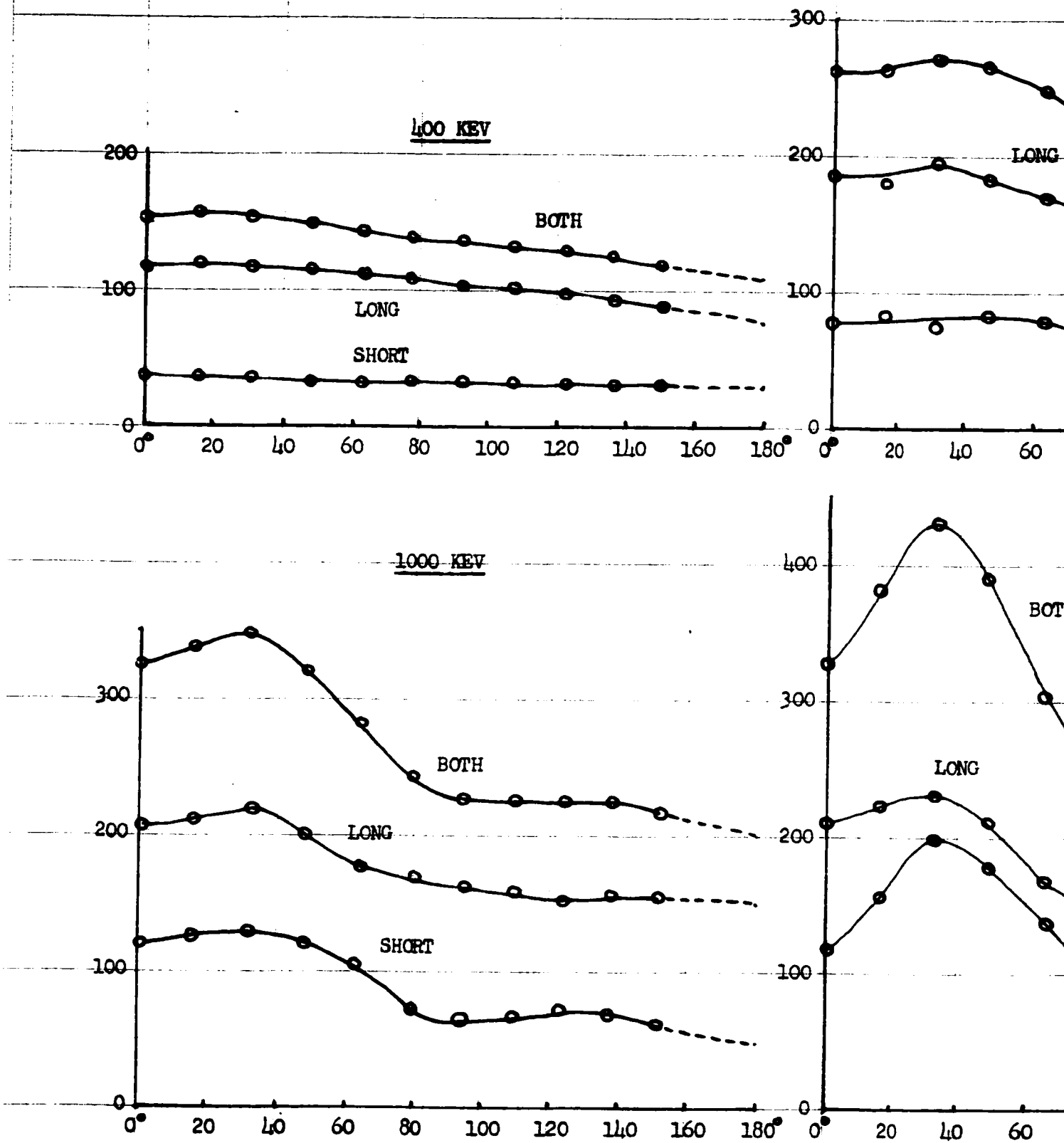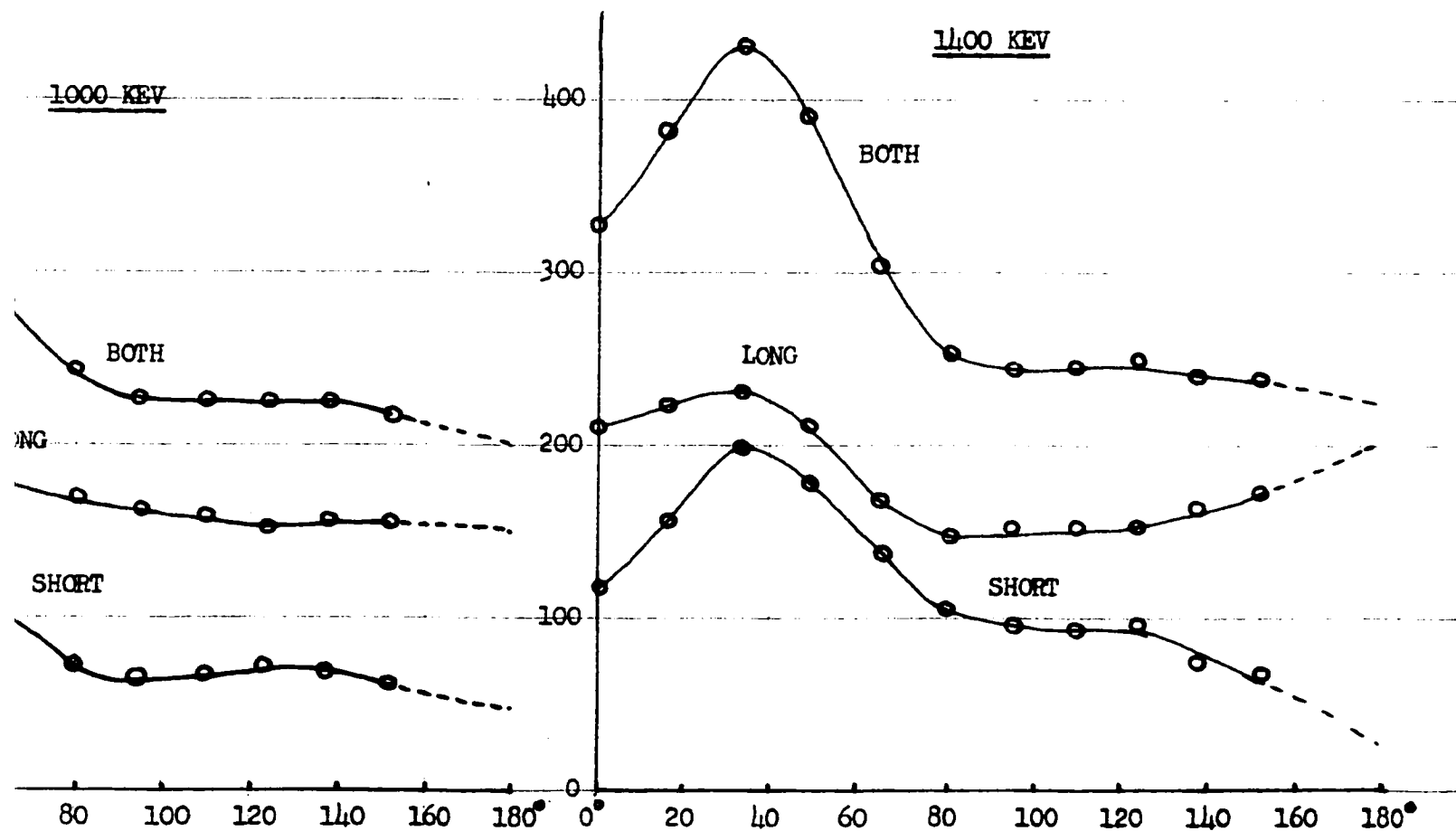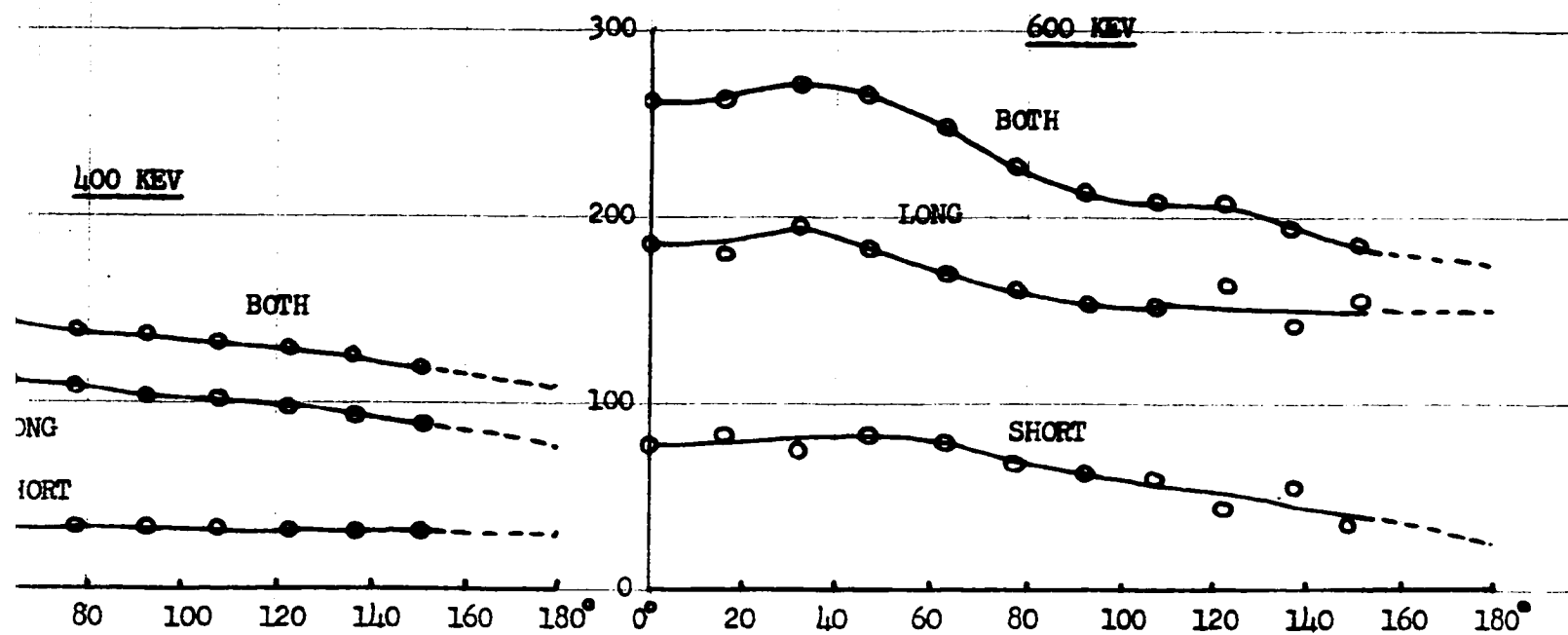
FIG 4. PROTON ANGULAR DISTRIBUTION AT FOUR BOMBARDING ENERGIES. PROTO[N]
UNITS) PLOTTED AS A FUNCTION OF THE ANGLE OF OBSERVATION (C. M. COORDI[NATES)]

PROTON ANGULAR DISTRIBUTION AT FOUR BOMBARDING ENERGIES. PROTON COUNTING RATE (ARBITRARY

OTTED AS A FUNCTION OF THE ANGLE OF OBSERVATION (C. M. COORDINATES).

TABLE I

LEGENDRE COEFFICIENTS IN THE
EXPANSION OF PROTON ANGULAR DISTRIBUTIONS

		Both Groups	Long Group	Short Group
400 kev	A_0	248	187	61
	A_1	28	28	<1
	A_2	<1	-3	2
	A_3	8	10	-2
	A_4	-7	-7	<1
	A_5	-1	<1	<1
	A_6	-3	-1	-1
600 kev	A_0	398	289	109
	A_1	84	40	44
	A_2	15	28	13
	A_3	-1	-2	<1
	A_4	-31	-13	-17
	A_5	-11	-10	-1
	A_6	6	-5	11
1000 kev	A_0	448	302	146
	A_1	123	57	66
	A_2	66	35	31
	A_3	6	4	<1
	A_4	-53	-13	-39
	A_5	-16	-12	-4
	A_6	-7	-17	10
1400 kev	A_0	485	290	195
	A_1	155	53	102
	A_2	104	73	31
	A_3	<1	4	-3
	A_4	-88	-24	-64
	A_5	-77	-35	-42
	A_6	-29	-24	-5

The accuracy of these coefficients depends of
course on the accuracy of Y(cos θ) and also on the close-
ness of fit of the analytic approximate curve to Y(cos θ).
This last source of error is small as can be seen from the
fact that the value of $\frac{13}{2}\int_{-1}^{+1} P_6(\cos\theta)\, A(\cos\theta)$ obtained by
this method is 0.011, instead of its actual value zero.
We may conclude that the method of calculation introduces
an error no larger than a few per cent of A_0.

The calculated coefficients in arbitrary units
have been plotted as a function of bombarding energy in
Fig (5). For the two groups together, the case of best
experimental accuracy, the coefficients show a uniform
variation with energy. For the individual groups, the
same general behavior is apparent, with slight differences
that are probably due to experimental inaccuracy. As yet
thereis no satisfactory theory of the angular distribution
of particles emitted in the decay of the compound nucleus.
However, from very general arguments, one can arrive at a
few conclusions concerning the distribution. First, the
fact that the distribution is not spherically symmetric
means that a direction must be established in the compound
nucleus with reference to which the asymmetry can exist.
The target nuclei and bombarding nuclei have but one
directional property, their spin axes, and we suppose that
these are randomly oriented. For those collisions in which
the bombarding nuclei have some angular momentum about the
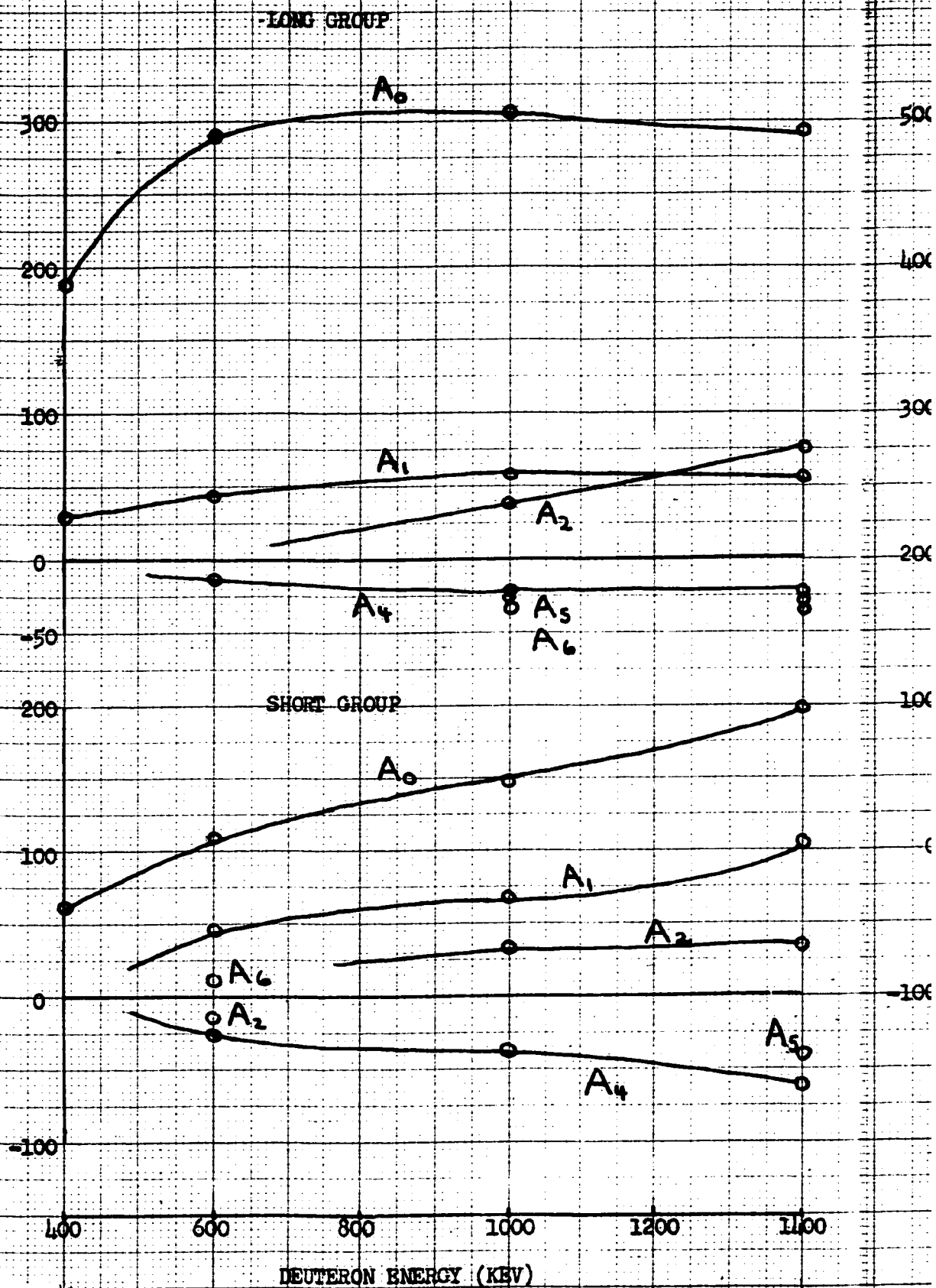
FIG 5. LEGENDRE COEFFICIENTS PLOTTED AS A FUNCTION OF DEUTERON ENERGY. ERRORS NOT SHOWN ON THE GRAPH ARE LESS THAN ±10.

BOTH GROUPS

A_0

A_2

A_5

A_6

A_1

A_3

A_1

A_3

A_6

A_5

A_4

A_5

A_4

DEUTERON ENERGY (KEV)
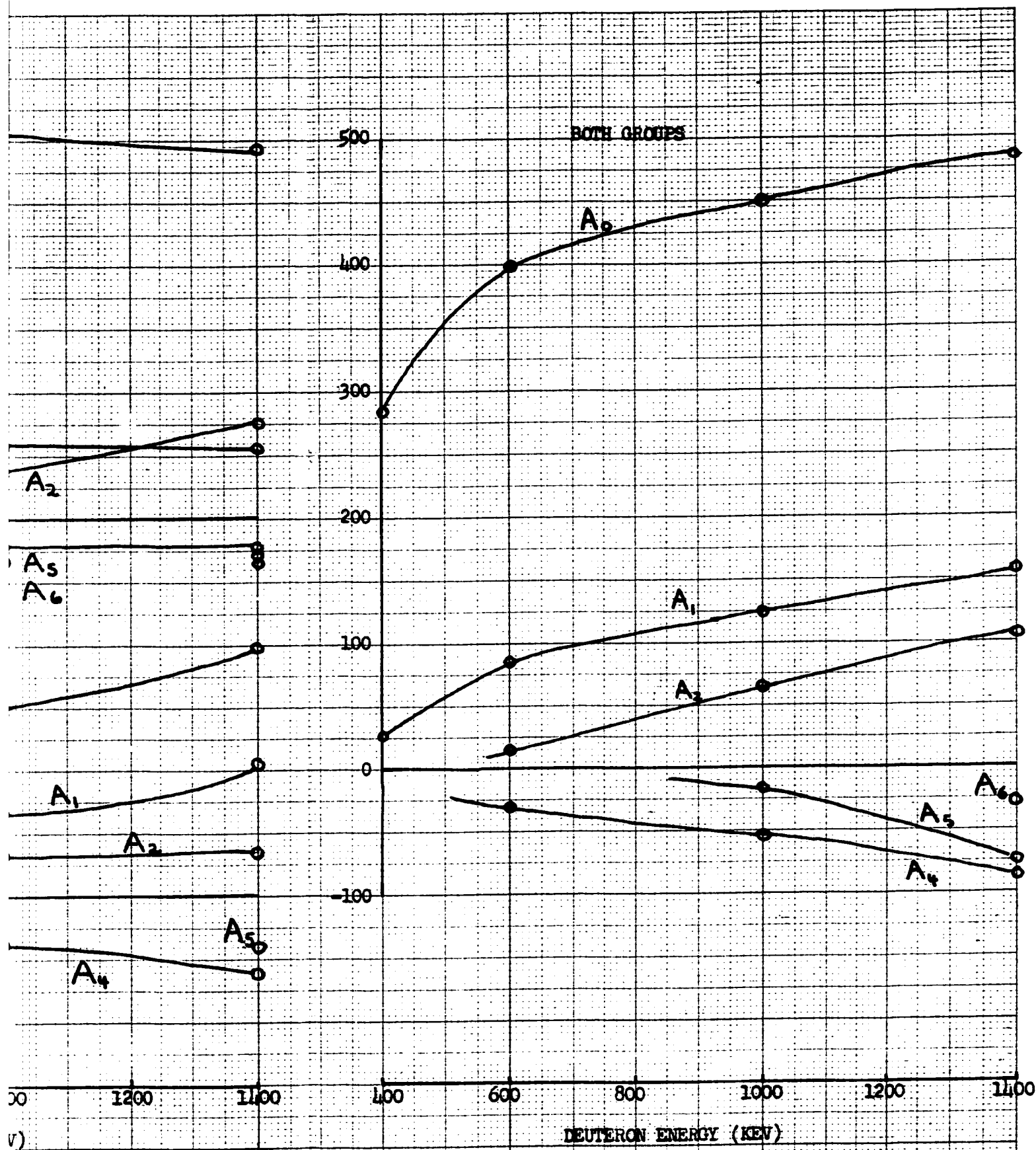
...ENTS PLOTTED AS A FUNCTION OF DEUTERON ENERGY.   COEFFICIENTS NOT APPEARING

...LESS THAN ±10.

target nuclei, the angular momentum vectors will all lie
in a plane normal to the beam of bombarding nuclei, and
in this way the direction of the beam is defined, but not
its sense. Thus the possibility exists of a distribution
that is a function of the angle between the direction of
emission and this equatorial or normal plane, but since
the sense of the beam is not defined, the distribution should
be symmetric with respect to this plane. There is some
experimental evidence that this is actually the form of
the distribution observed for particles emitted from an
isolated resonance level in the compound nucleus, an energy
level that is well separated from adjacent levels in the
energy spectrum. Asymmetry about this equatorial plane,
such as we have found for the protons, is supposed to
result from the interference of the wave functions associated
with the emitted particles. This interference between the
angular dependent components of the wave function apparently
takes place when the wave function contains terms that refer
to more than one angular momentum. To calculate the distri-
bution resulting from such interference requires a more
detailed knowledge of the wave functions than is yet avail-
able.

Inglis (3) ⁻⁻, ²⁰⁻) has proposed that if the
experimental distribution is expanded in terms of the
Legendre polynomials, the highest order polynomial appear-
ing in the expansion will be of order 2L, where L is the

highest orbital angular momentum quantum number involved
in the outgoing waves. The angular momentum of the emitted
particles is not known, but possible allowed values of the
angular momentum can be calculated from the spins and orbital
angular momenta of the particles involved in the reaction
by applying the principle of conservation of total angular
momentum. These possible values can often be further
restricted by the application of certain so-called selection
rules, so that in some cases the allowed values can be
narrowed down to only one or two.

Consider the reaction $Li^6 + H^2 \rightarrow (Be)^* \rightarrow Li^7 + H^1$, in
which the Li^7 nucleus is left in its ground state of odd
parity, and first suppose that only deuterons with zero
orbital momentum about the Li^6 nucleus take part in the
reaction. We will denote the spin of nucleus A by $s(A)$,
the internal orbital angular momentum by $\ell(A)$, and the
resultant total angular momentum of the nucleus by $j(A)$.
The resultant total spin of a system of two nuclei A and
B will be denoted by $S(A + B)$, the total orbital momentum
by $L(A + B)$, which will include both internal angular
momentum of the nuclei A and B and the orbital momentum of
the two particles about their common center of mass, and
we will denote the total angular momentum of the system
by $J(A + B)$. For the particles in the reaction above the
following values are currently accepted:

$$s(H^2) = 1 \qquad s(H^1) = \tfrac{1}{2} \qquad s(Li^6) = 1 \qquad j(Li^7) = 3/2$$

$$\ell(H^2) = 0 \qquad\qquad\qquad\qquad \ell(Li^6) = 0$$

The total angular momentum of Li^7, commonly referred to as
its 'spin' is thought to be 3/2 from measurements of its
band spectra and from magnetic resonance data[19], but how
this momentum is divided between spin and internal orbital
motion is not known. One might normally suppose that for
the ground state of a nucleus, the orbital momentum would
likely be zero, in which case $s(Li^7) = 3/2$. We will con-
sider first the allowed values of proton momentum on this
assumption that the ground state of Li^7 is a ^4S state, and
then consider alternative assumptions.

Since $s(Li^6) = 1$, and $s(H^2) = 1$, then $S(Li^6 + H^1) = 0$,
or ± 2. We are supposing that only s-deuterons take part
in the reaction, so that $L(Li^6 + H^2) = 0$, and
$J(Li^6 + H^2) = 0, \pm 2$. These values can arise from the follow-
ing combinations:

(1) $s(Li^7) = \tfrac{3}{2}$, $s(H') = -\tfrac{1}{2}$, $S(Li^7 + H') = 1$
Proton orbital mom. $= -1$ $L(Li^7 + H') = -1$ $\Big\}$ $J(Li^7 + H') = 0$

(2) $s(Li^7) = \tfrac{3}{2}$, $s(H') = \tfrac{1}{2}$, $S(Li^7 + H') = 2$
Proton orbital mom. $= -2$, $L(Li^7 + H') = -2$ $\Big\}$ $J(Li^7 + H') = 0$

(3) $s(Li^7) = \tfrac{3}{2}$, $s(H') = \tfrac{1}{2}$, $S(Li^7 + H') = 2$
Proton orbital mom. $= 0$, $L(Li^7 + H') = 0$ $\Big\}$ $J(Li^7 + H') = 2$

(4) $s(Li^7) = \frac{3}{2}$ $s(H') = -\frac{1}{2}$ $S(Li^7 + H') = 1$
Proton orbital mom $= 1$ $L(Li^7 + H') = 1$ $\Big\} J(Li^7 + H') = 2$

(5) $s(Li^7) = \frac{3}{2}$ $s(H') = \frac{1}{2}$ $S(Li^7 + H') = 2$
Proton orbital mom $= -4$ $L(Li^7 + H') = -4$ $\Big\} J(Li^7 + H') = -2$

(6) $s(Li^7) = \frac{3}{2}$ $s(H') = -\frac{1}{2}$ $S(Li^7 + H') = 1$
Proton orbital mom $= -3$ $L(Li^7 + H') = -3$ $\Big\} J(Li^7 + H') = -2$

Possible values of proton orbital mom $= 0, \pm 1, \pm 2, \pm 3, \pm 4$.

These possible values of ℓ are calculated simply on
the basis of conservation of total angular momentum, and
allowing any exchange of energy between spin and orbital
momentum. An additional restriction on the momenta is the
rule that the parity of the wave function describing the
initial system (target nucleus plus bombarding particle)
must be the same as the parity describing the final con-
figuration in the reaction. The parity of such a system
is made up of two parts, the intrinsic parity of the nuclei
in the system and the parity of the wave function describing
their relative motion, and

these parities combine in the following way: (odd)+(odd)= (even)+(even) is even, (even)+(odd) is odd. The parity of Li^6 is even, the parity of the deuteron is even, and since we are considering entering s-deuterons, the parity of the left hand side of the reaction is even. The parity of Li^7 is supposed to be odd, the intrinsic parity of the proton is even, so that to conserve parity across the reaction, it is necessary that the emitted proton have odd angular momentum about the Li^7 nucleus. This excludes the even possible values above, and leaves the values $\ell = \pm 1, \pm 3$. as the possible values of angular momentum quantum number in the outgoing proton waves. A similar analysis for entering p-deuterons shows that the allowed values in this case are $\ell = 0, \pm 2, \pm 4$.

Now consider how these allowed values of ℓ fit Inglis' supposition that the highest order Legendre poly- nomial in the angular distribution is twice the largest angular momentum quantum number present in the outgoing waves. The highest order experimental coefficient is A_6; at 1.4 mev this coefficient is sufficiently large that it .cannot be attributed to experimental error. This is con- sistent with the $\ell = 3$ value above, for entering s-deuterons, but s-deuterons alone do not determine a direction and should lead to a spherical distribution. Apparently we must con- sider entering p-deuterons, at least, which would lead to a P_8 term in the distribution. It is not surprising that no

such term is observed, since it would be proportional to the penetrability of an entering p-deuteron multiplied by the penetrability of the emitted g-proton, and would be very small at these energies. Thus the observed distribution is not inconsistent with our assumed value for the spin of Li^7 to be 3/2.

Another feature of the experimental results that is consistent with this interpretation is the fact that A_6 is negative. The assumption that the highest order of the polynomials appearing in the expansion is twice the highest angular momentum quantum number present in the outgoing waves is suggested by analogy to the form of the angular distribution for nuclear scattering. A nuclear scattering reaction and a substitutional reaction (one in which bombarding and emitted particle are different) are quite different in many respects, but if the two problems are treated with the same mathematical formalism it is reasonable to suppose that the distribution in both cases might be expressed in the same general form. The angular distribution for nuclear scattering has been worked out by Mott and Massey[2] to be

$$(1) \quad \sigma(\theta,E) \propto \left| \sum_{\ell} (2\ell+1) \, S_{\ell}(E) \, P_{\ell}(\cos\theta) \right|^2$$

where $\ell\hbar$ is the angular momentum of the incident particle about the scattering center and $S_{\ell}(E)$ is a complex function of E, the energy of the bombarding particle. The exact form of $S_{\ell}(E)$ depends on the nature of the interaction between the scattered particle and the scattering center,

but it approaches zero rapidly for large ℓ , so that the sum in Eq. (1) usually has only a few significant terms, and in the square of the sum the highest term will contain P_{2L} where $L\ell$ is the highest angular momentum the incident particle can have and yet be appreciably scattered.

Now if we suppose that the angular distribution of particles from a substitutional reaction can be expressed in the same form, with, of course, a different function $S_\ell(E)$, the sum over ℓ would then include all values of ℓ present in the outgoing wave, and in the square of the sum the highest order term would be of order twice the highest angular momentum quantum number present in the outgoing wave. However, the coefficient of this highest even term should be positive. Lower order terms are due to cross products in the sum, which arise in taking the absolute value, and correspond to interference between waves of different angular momentum. Thus the presence of a negative P_6 term would indicate the presence of at least one higher even term, such as the P_8 term which should be present for entering p-deuterons.

As we have mentioned previously, only the total angular momentum of the Li^7 nucleus is known, $j(Li^7) = 3/2$. We have seen that the assumption that this momentum is entirely due to spin is consistent with the experimental results for the angular distribution of the protons, and we now consider the alternative assumption, $s(Li^7) = \frac{1}{2}$,

$\ell(\text{Li}^7) = 1$. If one permits all possible exchanges of energy between spin and orbital angular momentum, this $^2P_{3/2}$ state leads to the same allowed values of ℓ for the protons as the $^4S_{3/2}$ state we have considered previously. However, as we shall point out in the section on the alpha particle excitation curve, the reason for assuming that $s(\text{Li}^7) = \frac{1}{2}$ is that other evidence indicates that there should be small interaction between spin and orbital momentum, i.e., that strict Russell-Saunders coupling applies to the momenta vectors. With this added restriction, we get as allowed values of ℓ for entering s-deuterons only ± 1. As before, we have $S(\text{Li}^6 + \text{H}^2) = S(\text{Li}^7 + \text{H}^1) = 0, \pm 2$, and in addition, $L(\text{Li}^6 + \text{H}^2) = L(\text{Li}^7 + \text{H}^1) = 0$. The only two possibilities that satisfy these conditions are:

(1) $s(\text{Li}^7) = \frac{1}{2}$ $\quad s(\text{H}^1) = -\frac{1}{2}$ $\quad S(\text{Li}^7 + \text{H}^1) = 0$
$\quad\quad \ell(\text{Li}^7) = 1$ $\quad$ proton orbital momentum $= -1$, $\quad L(\text{Li}^7 + \text{H}^1) = 0$

(2) $s(\text{Li}^7) = -\frac{1}{2}$ $\quad s(\text{H}^1) = \frac{1}{2}$ $\quad S(\text{Li}^7 + \text{H}^1) = 0$
$\quad\quad \ell(\text{Li}^7) = -1$ $\quad$ proton orbital momentum $= 1$, $\quad L(\text{Li}^7 + \text{H}^1) = 0$

These values of $\ell = \pm 1$ for the proton also satisfy parity requirements. For entering p-deuterons, we have $\ell = 0$, or ± 2. To get a term as high as P_6 in the distribution requires entering d-deuterons which lead to $\ell = \pm 1, \pm 3$.

This result is in agreement with the present interpretations of the angular distributions of the alpha particles from the $\text{Li}(\text{d-}\alpha)\alpha$ reaction. Heydenburg, Hudson, Inglis, and Whitehead[3] have measured the angular distribution over the deuteron energy range 0.5 to 3.5 mev.

Inglis[4] has interpreted their results to show that over this entire energy range the presence of entering d-deuterons is necessary to explain the observed distribution. This broad level in Be^8 excited by d-deuterons would also be expected to decay by proton emission, and would account for the P_6 term in the proton distribution.

Thus it appears that either assumption regarding the spin of Li^7, $S(Li^7) = \frac{1}{2}$ or $S(Li^7) = 3/2$ is consistent with the appearance of terms of order up to P_6 in the angular distribution within the meagre restrictions of our present qualitative theory of the phenomenon. Definite interpretation of these experimental results must await the development of a more adequate theory. The previous discussion concerning the allowed values of angular momentum is restricted to the long group of protons produced in the reaction in which the Li^7 nucleus is left in its ground state of odd parity. A similar analysis for the short group is not possible since the various momenta and parity of the excited state are not known. Wigner and Feenberg[18] have shown from theoretical arguments that this state is likely a $^2P_{\frac{1}{2}}$ state. As Bethe[7] has pointed out, this is in agreement with the observed intensities of the two groups, long/short $\approx 2/1$, on the theory that the partial width for emission of a particle leaving the residual nucleus in a state with angular momentum j is proportional to $2j + 1$, the multiplicity of the state, or in quantum
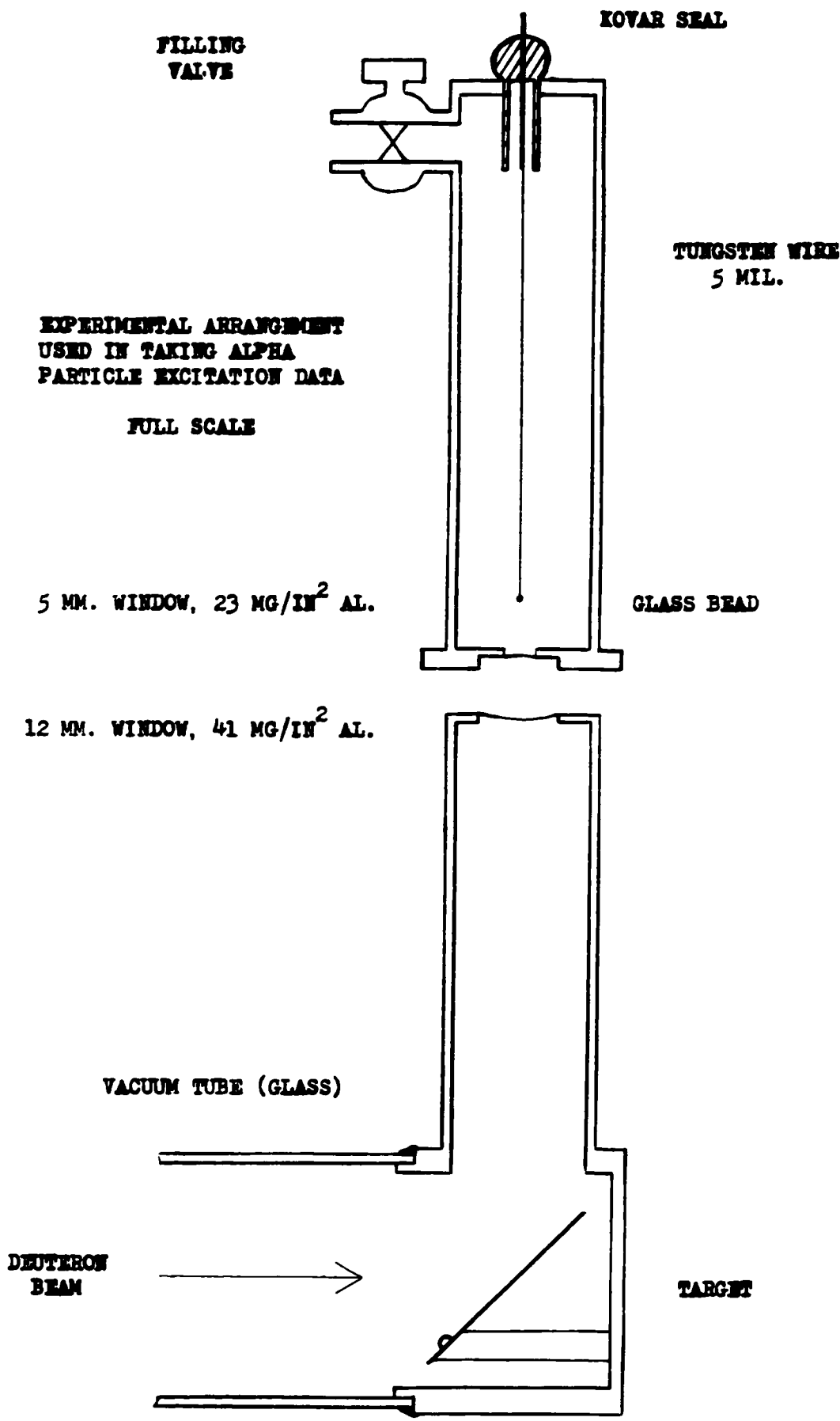
mechanical terms, the degeneracy of the state. If we assume that this excited state of Li^7 is a $^2P_{\frac{1}{2}}$ state with odd parity, the allowed values of ℓ for the short group of protons are the same as for the long group, assuming either Russell-Saunders coupling or allowing exchange of spin-orbit momentum. This is consistent with the observed distributions, which show a great similarity between the two groups.

5. ALPHA PARTICLES EXCITATION FUNCTION

The alpha particles observed when a Li^6 target is bombarded by deuterons have been identified by Oliphant, Shire, and Crowther[1] with the reaction

$$Li^6 + H^2 \rightarrow (Be^8)^* \rightarrow He^4 + He^4 + 22.2 \text{ MEV}.$$

The Q value above is calculated from the masses of the nuclei involved in the reaction. The mean range of the alpha particles in air has been determined by Rutherford[10] to be 12.7 cm for deuterons of 190 kev, and because of the high Q value for this reaction the range of the alphas varies only slightly with deuteron energy. The excitation curve for emission of alpha particles at right angles to the deuteron beam has been measured for deuteron energies between 190 kev and 1600 kev using the experimental arrangement shown in Fig (6). The target is a thin film of $Li_2^6SO_4$, 106 microgm/cm^2 thick, evaporated in vacuum on to a silver disc thick enough to stop the deuteron beam

FILLING
VALVE

KOVAR SEAL

TUNGSTEN WIRE
5 MIL.

EXPERIMENTAL ARRANGEMENT
USED IN TAKING ALPHA
PARTICLE EXCITATION DATA

FULL SCALE

5 MM. WINDOW, 23 MG/IN^2 AL.

GLASS BEAD

12 MM. WINDOW, 41 MG/IN^2 AL.

VACUUM TUBE (GLASS)

DEUTERON
BEAM

TARGET

FIG, 6

completely. The disc is placed in the beam at a 45° angle,
and the alphas are observed at 90° to the beam as shown
in the figure. Two thin aluminum windows admit the alphas
from the target chamber into the counter. The counter is
a simple proportional counter with a round window 5 mm in
diameter in the center of one end. The counter is constructed
of brass with a 2.2 cm I. D. cathode; the central wire is
5 mil tungsten. The counter was filled with one-half
atmosphere of commercial argon, and operated at 300 volts.
The signal from the counter was amplified in a linear
amplifier (Atomic Inst. Co., Model 204-A) with a 0.2 micro-
second rise time and then fed into a discriminator (Atomic
Inst. Co., Model 101-A). The discriminator output was
recorded on a register through a scale of 64.

The only other long range alpha particles from
the Li_2SO_4 target are from the Li^7 impurity, by the reaction
$Li^7 + H^2 \rightarrow (Be^9)^* \rightarrow He^4 + He^4 + n^1 + 14.9$ mev. The maximum
range of these alpha particles has been measured by
Oliphant[16] to be 8.0 cm for 160 kev deuterons. Although
the difference in ranges of the alphas from Li^6 and Li^7
is approximately the same as the difference in ranges of
the two proton groups from Li^6, the range straggling is
much less for the alphas than for the protons, and it was
not difficult to separate the two groups of alphas by
placing the proper amount of aluminum absorber between
the counter and the target. The protons from Li^6 then

pass all the way through the counter, but in a proportional counter, the voltage pulse produced by a proton is only about one fourth as large as the pulse produced by an alpha particle, so that the proton counts could be readily biased out with the discriminator.

The excitation curve for the alpha particles is plotted in Fig (7). The separation between adjacent points on the curve is approximately one-third of the target thickness, and each point represents a count of at least 2560 alpha particles. At bombarding energies below 600 kev a molecular deuteron beam was used.

With this same experimental arrangement and target the excitation curve for both groups of protons from Li^6 was taken again, by adding enough absorber to stop all the alpha particles and let both groups of protons through, and lowering the discriminator bias to a value just high enough to exclude gamma ray counts. The results are also plotted in Fig (7) for comparison of the cross section of the two reactions. Both curves are plotted on the same scale and indicate the relative probability for the decay of Be^8 by emission of an alpha particle or of a proton into unit solid angle at $90°$. The $Li^6(d, \alpha)\alpha$ reaction is a so-called probable reaction. A reaction involving light nuclei may be considered probable if: (1) Parity is conserved across the reaction, (2) total angular momentum is conserved, (3) the penetrability of entrant and emitted particles is
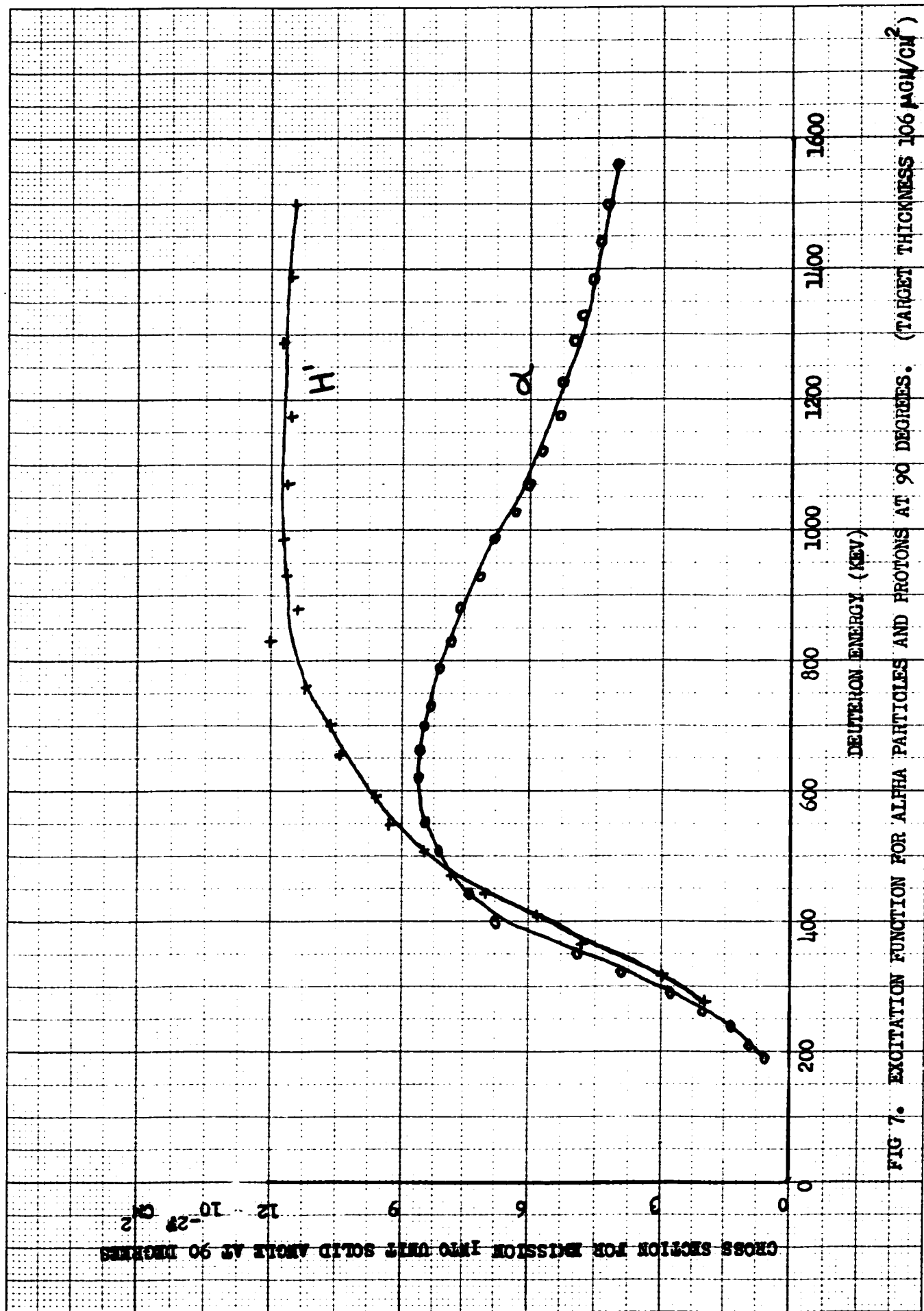
FIG 7. EXCITATION FUNCTION FOR ALPHA PARTICLES AND PROTONS AT 90 DEGREES. (TARGET THICKNESS 106 μGM/CM^2)

high, (4) the resultant spin of the target nucleus -
bombarding particle system is equal to the resultant spin
of the emitted particle - residual nucleus system. This
last condition is met when there is no exchange of energy
between the spin and orbital momenta of the nucleons in
the reaction.. Goldhaber[6] has pointed out that the
interaction between the magnetic momenta of the nucleons,
the only interaction that could bring about such an exchange
of energy, is only on the order of 1 kev, very small com-
pared to the other forces acting in the reaction. Conse-
quently the probability of such an interaction is small, and
a reaction which requires the spin-orbit interaction in
order to satisfy conditions (1) or (2) above will be improb-
able. Fig (7) shows that the probability of the $Li^6(d_rp)Li^7$
is about the same as for the $Li^6(d - \alpha)\alpha$ reaction, hence
the $Li^6(d-p)Li^7$ reaction may be considered a probable
reaction. Bethe[7] has interpreted this to mean that the
$Li^6(d-p)Li^7$ reaction obeys the four requirements for a
probable reaction listed above, from which it follows that
the spin quantum number of Li^7 is $\frac{1}{2}$. To satisfy condition
(3) at low bombarding energies, the entrant deuteron should
have $\ell = 0$. To satisfy condition (1) the emitted proton
must have odd angular momentum, and since $L(Li^7 + H^1) = 0$,
the Li^7 nucleus must have internal angular momentum equal
and opposite to the angular momentum of the emitted proton.
For the ground state of a nucleus, orbital angular momentum
1 seems more likely than any higher odd value, and this
leads to the result $s(Li^7) = \frac{1}{2}$, $\ell(Li^7) = 1$.

The excitation curve for the α-particles at $90°$ shows a broad maximum in the neighborhood of 600 kev deuteron energy. The curve in this region does not have the familiar resonance shape, but at these low bombarding energies the penetrability of the incident deuteron through the potential barrier at the Li^6 nucleus will determine the shape of the curve to a large extent. The shape of the excitation curve in the neighborhood of a single resonance may be expected to follow the Breit-Wigner one level formula[8]:

$$\sigma = \frac{\pi \lambda^2 \; \Gamma_\alpha \; \Gamma_{H^2}}{(E-E_R)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

where Γ_α is the partial width of the level for emission of alpha particles

Γ_{H^2} is the partial width of the level for capture of deuterons

λ = (wavelength of incident deuteron)/2π

Γ is the total width of the level for decay by any process, and is equal to the sum of all the partial widths

E = energy of the bombarding deuteron

E_R = energy of bombarding deuteron which excites the compound nucleus to the resonance energy.

Γ_{H^2} is proportional to $P_{H^2}(E, \ell)$, the penetrability of the deuteron through the potential barrier at the nucleus; and this penetrability depends on the deuteron energy E and its angular momentum ℓ about the target nucleus. There is a similar penetrability factor in Γ_α, but the energy of the alpha particles in this reaction is so high that this factor

is practically independent of the deuteron energy. Since $\lambda^2 \propto \frac{1}{E}$, the dependence of the excitation curve on deuteron energy can be expressed

$$(1) \qquad \sigma \propto \frac{1}{E} \frac{P_{H^2}(E,\ell)}{(E-E_R)^2 + (\frac{\Gamma}{2})^2}$$

and the function

$$(2) \qquad \frac{\sigma E}{P_{H^2}(E,\ell)} \propto \frac{1}{(E-E_R)^2 + (\frac{\Gamma}{2})^2}$$

will then have a simple resonance shape in the neighborhood of an excited state of the compound nucleus, with its peak at E_R and a width at half maximum equal to Γ .

To calculate this function $\frac{\sigma E}{P_{H^2}(E,\ell)}$ it is first necessary to calculate $P_{H^2}(E, \ell)$. Gamow[7] has derived an approximate expression for the penetrability of a particle with charge z through the Coulomb barrier at a nucleus of charge Z. For the case of $\ell = 0$

$$P_{H^2}(E, \ell = 0) = \exp\left[-\frac{4\pi z Z e^2}{\hbar v}\left\{ \text{arc cos} \sqrt{\frac{E}{B}} - \sqrt{\frac{E}{B}(1-\frac{E}{B})}\right\}\right]$$

where E and v are the energy and velocity of the deuteron in center of mass coordinates and B is the height of the Coulomb barrier; $B = zZe^2/R$, where R is the nuclear radius. This formula does not hold for deuteron energies near the barrier height, for setting E = B the formula above gives P = 1, whereas on the quantum mechanical picture there should be a finite probability that the particle is reflected by the barrier. We will restrict the use of this formula to deuteron energies much less than B. We consider only the

case of $l = 0$ since at deuteron energies below 1 mev the penetrability factor for s-deuteron is more than thirty times greater than the penetrability of d-deuterons (p-deuterons do not take part in this reaction).

The difficulty with using this formula to calculate the deuteron penetrability is that the value of R is uncertain. The 'radius' R appearing in the expression for the barrier height is the distance from the center of the nucleus at which the repulsive electrostatic forces are overcome by the attractive nuclear forces, and it is generally assumed to be equivalent to the value of the nuclear radius determined from fast neutron cross section measurements and, indirectly, by calculation from the difference in binding energies of neighboring isobars. The radii of those light nuclei which have been measured by these methods can be fitted fairly well to the formula $R_m = 1.5 A_m^{1/3} 10^{-13}$ cm, where R_m is the radius of the nucleus of mass number A_m(8). This formula describes the average variation of radius with mass number, but for particular nuclei some deviation from the average may be expected, as in the case of the average variation of binding energy with mass number. This formula gives for Li^6 a radius $R = 2.7 \times 10^{-13}$ cm, and a Coulomb barrier height $B = 1.58$ mev. Using these values we have calculated $P_{H^2}(E,0)$ and the function $\frac{\sigma \epsilon}{P_{H^2}}$, using the experimental value of σ from the excitation curve at 90°. The use of the cross section for emission of an alpha particle into unit solid angle at 90° instead of the total

cross section for alpha particle emission is justified
since the angular distribution of the alphas has been
shown to be very nearly spherically symmetrical at the
low bombarding energies we are concerned with (3). The
function $\frac{\sigma_{exp} E}{P_{H^2}}$ is plotted in Fig (8) as the solid curve.
The function σ_{exp} is included for comparison, the dotted
curve. The familiar resonance shape is quite apparent.

To determine the effect of the uncertainty in R
on this calculated function we have repeated the calcula-
tion using the value R = 3.77 x 10^{-13} cm. The function
$\frac{\sigma_{exp} E}{P}$ obtained with this value of R is plotted in Fig (8)
as the dashed curve. If the range of the nuclear force
field about the Li^6 nucleus is actually 2.7 x 10^{-13} cm,
it seems reasonable to use a larger value in the calcula-
tion of the barrier height to take into account the range
of the field of force about the deuteron. This larger value
of R lowers the barrier height and increases the penetra-
bility by a factor of about 2, but has little effect on
the rate of change of P with E which determines the shape
of the $\frac{\sigma E}{P}$ curve. The solid curve in Fig (8) can be
fitted fairly well to a function of the form of Eq. (2) with
the values $E_R \approx$ 350 kev, Γ = 560 kev. To fit the dashed
curve the best values are $E_R =$ 380 kev, $\Gamma =$ 660 kev which
shows that the value chosen for R will produce slight change
in the values to be assigned to the width and location of
this level. The thickness of the target used in taking
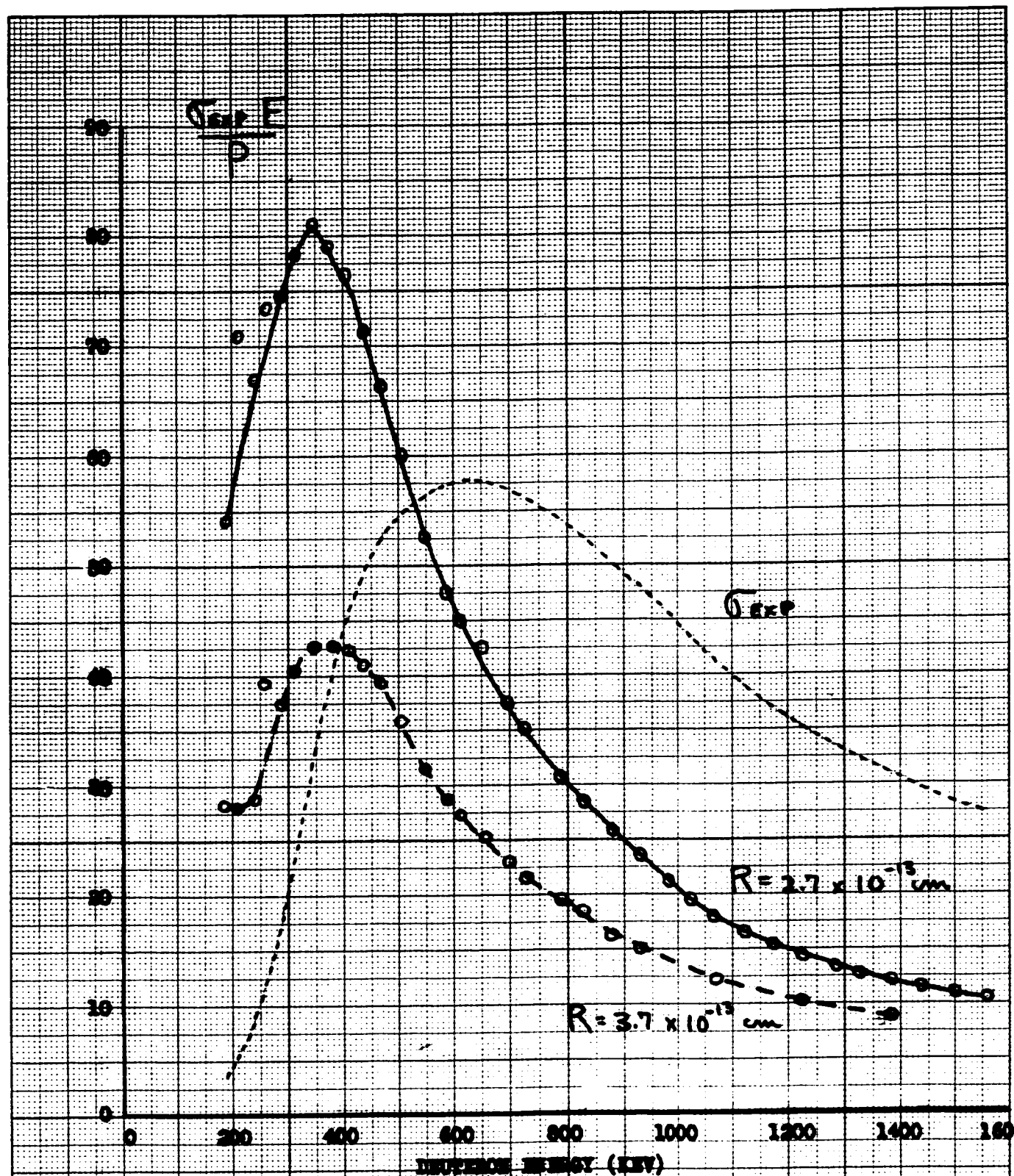this data is 106 micrograms of Li_2SO_4 per sq. cm. and a

FIG 8. ALPHA PARTICLE EXCITATION FUNCTION CORRECTED FOR DEUTERON PENETRABILITY.

350 kev deuteron loses about 60 kev of energy in passing
through the target. This target thickness shifts the
peak in the experimental curve to a deuteron energy higher
than the resonant deuteron energy by approximately 30 kev,
or one-half the energy spread of the deuteron in the target.
This 30 kev correction is an approximation, but it is
probably correct to within $\pm$ 15 kev. Using the mean value
E_R = 365 kev, and subtracting 30 kev to correct for the
target thickness, we find for the excitation energy of the
Be^8 nucleus at the resonance peak 22.20 - (3/4)(0.365-0.030)=
22.45 mev.

The excitation curves for the two proton groups
in Fig (3) do not show any indication of a peak. One would
ordinarily attribute the rise in the curve between 200 kev
and 800 kev to the increasing penetrability of the deuterons
in this region. However, the level in Be^8 that appears in
the alpha particle excitation curve should also decay by
proton emission, and the proton excitation curve, corrected
for the penetrability of the deuteron, would be expected to
show a peak at 365 kev. In Fig (9) are plotted the $\dfrac{\sigma_{exp}\, E}{P_{H^2}(E, \ell=0)}$
functions for the two proton groups, where σ_{exp} is the experi-
mental excitation function for emission of protons into unit
solid angle at $0°$, and $P_{H^2}(E, \ell = 0)$ is calculated from the
value $R(Li^6)$ = 2.7 x 10^{-13} cm. The curves have been extended
only up to 900 kev since at higher deuteron energies the
asymmetry of the proton angular distribution becomes so
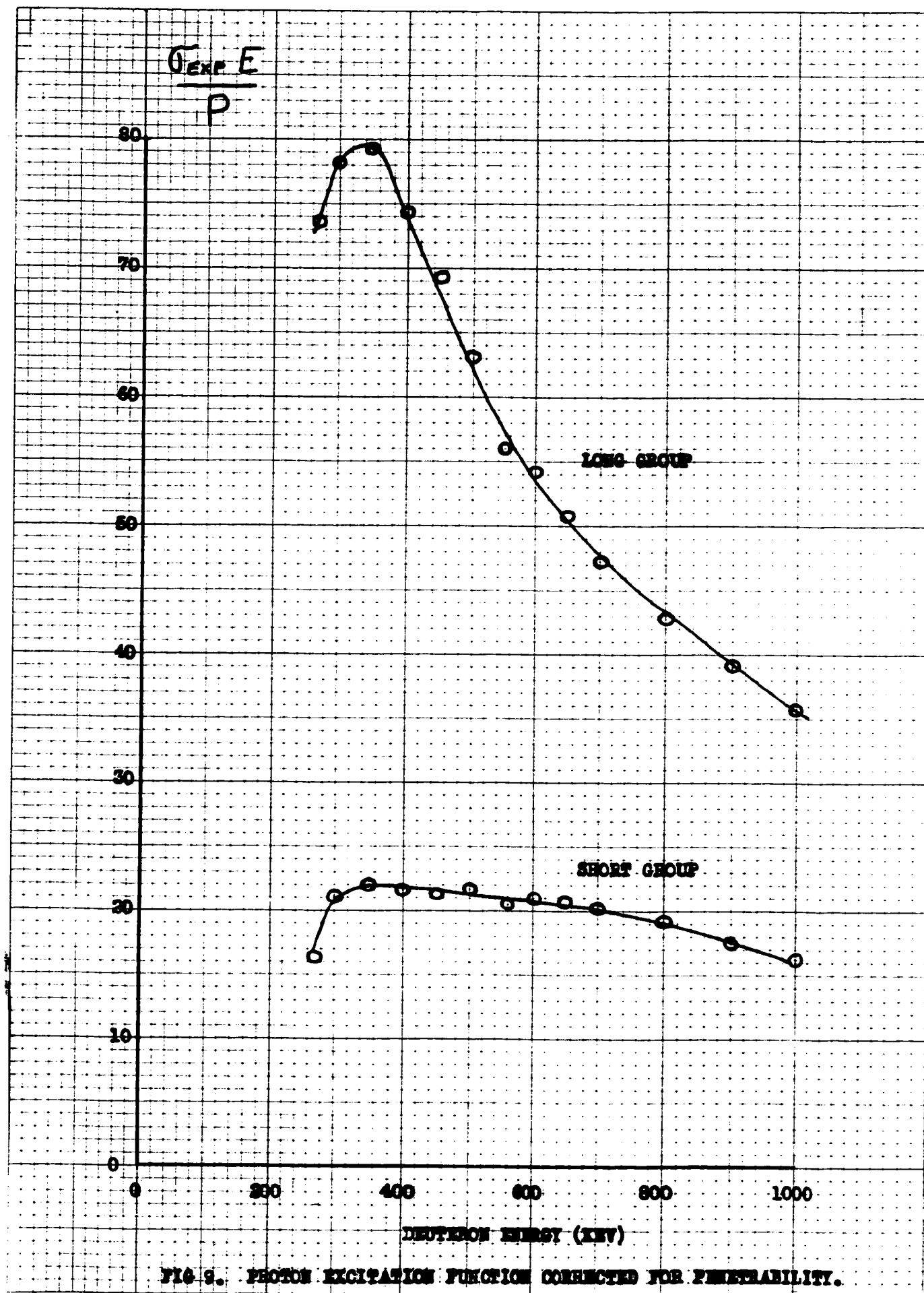large that the $0°$ excitation curve is no longer a good

FIG 9. PROTON EXCITATION FUNCTION CORRECTED FOR PENETRABILITY.

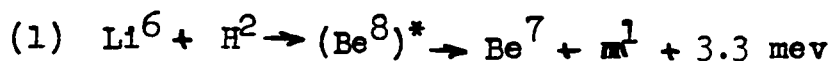approximation to the total cross section excitation curve.

The long range proton group does show this expected peak, in surprisingly good agreement with the alpha particle data in view of the large and somewhat uncertain correction that is made in obtaining the curves of Fig (9) from the curves in Fig (3). The curve for the short range proton group shows the same rise up to 350 kev but at higher energies it falls off very gradually. There is a slight indication of a broad maximum. As has already been emphasized, the accuracy of the experimental excitation functions is poor, and this is especially true for the short proton group at low energies, since the short group counting rate is the small difference between two larger counting rates. One is, therefore, reluctant to draw any definite conclusions concerning the short range protons from the curve in Fig (9).

The fact that the proton excitation curves in Fig (3) do not fall off above 700 kev as the alpha particle excitation function does may be interpreted to mean that there is another broad level in Be^8 at some higher deuteron energy that decays by proton emission, but not by alpha particle emission, i.e., the level appears in the proton excitation curve but not in the alpha particle excitation curve. This can be explained by the fact that alpha particles obey Bose-Einstein statistics, so that the two alpha particles produced in the decay of a Be^8 nucleus must have equal angular momentum[9]; hence only excited states of Be^8

with even angular momentum can decay by alpha particle emission. No such restriction applies to the protons in the $Li^6(d-p)Li^7$ reaction, so that a level in Be^8 somewhere above 365 kev that had odd angular momentum could show up in the excitation curve for the protons and yet not appear in the alpha particle excitation curve.

6. NEUTRON EXCITATION FUNCTION

The neutrons emitted in the decay of Be^8 are thought to come from the two reactions

(1) $Li^6 + H^2 \rightarrow (Be^8)^* \rightarrow Be^7 + n^1 + 3.3$ mev

(2) $Li^6 + H^2 \rightarrow (Be^8)^* \rightarrow He^4 + He^3 + n^1 + 1.7$ mev

The Q values are calculated from the mass differences, using Bethe's 1947 values for the nuclear masses[8]. The neutrons have been identified with these two reactions by Rumbaugh, Roberts, and Hafstad[15], using separated isotope targets, by measuring the energy of the neutrons and also by observing the activity of Be^7, which decays by K-capture.

It would be desirable to determine the excitation functions for these two reactions separately, but there are serious experimental difficulties. In the second reaction the compound nucleus breaks up eventually into three particles, and theoretically, on the basis of momentum and energy conservation, the neutron can have any energy from zero up to $7/8(1.7) = 1.5$ mev. The actual distribution will depend on the manner in which the reaction proceeds, which is not yet known. Rumbaugh's cloud chamber measurements from which

he identified the reaction indicate a rather sharp maximum in the energy spectrum at 1.1 mev (for deuterons of 800 kev), but his measurements did not include neutrons of energy less than 600 kev, and since he observed only 200 recoil tracks, his statistical accuracy is poor. The neutrons from the first reaction are monoenergetic, neglecting the slight spread due to target thickness, with 2.9 mev energy for zero deuteron energy. It would be possible to count the high energy group alone using a proportional counter and biasing out the lower energy neutrons from the second reaction. However, any method of detection sensitive to the broad energy range of the neutrons from the second reaction would also be sensitive to the monoenergetic group. A more serious problem encountered in measurements of the low energy neutrons is the large background of neutrons from sources other than the target. The background is due largely to deuteron bombardment of unavoidable carbon contamination, the various apertures that define the deuteron beam. The carbon reaction is endothermic, with a threshold at about 300 kev, and the 'targets' are thick. At a deuteron bombarding voltage of 2 mev the carbon neutrons would have a broad range of energy up to approximately 1 mev, which would cover the lower half of the energy spectrum of the continuous group. These neutrons would appear as a large and somewhat erratic background difficult to make allowances for. Any satisfactory method of detection must exclude these neutrons from carbon and hence an unknown fraction of the neutrons from the second reaction.

The method of detection used in these experiments was a proportional counter biased to count neutron of energy greater than 1 mev. The proportional counter was a glass walled Eck & Kreb Beta-ray counter filled with 95.5% pure commercial argon at a pressure of 29.5 inches of Hg. The diameter of the outer cylindrical electrode is 1.9 cm, and the effective volume is approximately 6 cm long. With this geometry and pressure, 1200 volts on the counter provided sufficient gas amplification. The voltage pulses from the counter were amplified in a linear amplifier (B. E. Watt design), then fed into a discriminator (Atomic Inst. Co., Model 101-A). The discriminator output then drove a recorder through a conventional scale of 64. The counter was placed inside a brass tube with one-sixteenth inch walls, and was surrounded on three sides by approximately one inch of paraffin. The uncovered side of the counter cylinder was placed as close as possible to the target and in line with the deuteron beam, the actual distance between counter wall and target was about 1 cm.

The choice of argon was dictated by the necessity of keeping the range of the recoil nuclei short compared to the dimensions of the counter without increasing the pressure of the gas in the counter to such an extent that the voltage required for sufficient gas amplification is inconveniently high. The energy of the argon recoil depends on the angle between its path and the path of the incident

neutron, but its maximum value is .095 the energy of the incident neutron. Thus for a 1 mev deuteron the range of the argon recoils would be less than 1.3 mm[11]. Since the counter was 1.9 cm in diameter, nearly all of the recoils would lose all their energy in the gas in the counter, few would strike the walls, a necessary condition for maximum counter efficiency.

The bias was chosen so as to exclude the carbon neutrons. The actual value of the bias was determined from the bias curve for the Li^6 neutrons. At a constant bombarding voltage, the counting rate (number of neutron counts per incident deuteron) was determined as a function of the discriminator bias voltage. The counting rate decreases as the bias voltage is increased, and the bias voltage V at which the counting rate just vanishes is the amplitude of the largest voltage pulses produced in the counter. These largest pulses are produced by the $0°$ recoils from the high energy monoenergetic group of neutrons whose energy E can be calculated from the Q value and the known bombarding voltage. For a proportional counter the pulse size is proportional to the energy of the recoil, so that if a bias V will discriminate out all counts due to neutrons of energy less than E, a bias $V' = \frac{1.0}{E} V$ will bias out all counts due to neutrons of energy less than 1.0 mev. The bias necessary to exclude neutrons of energy less than 1 mev was determined in this way and held constant throughout the experiment.

The sensitivity of a biased proportional counter as a neutron detector is a function of the neutron energy. For neutrons of energy less than the bias energy B, the sensitivity is zero. For neutrons of energy $E > B$ it has been shown[12] that the sensitivity is proportional to $\sigma(E) \times (1 - B/E)$, where $\sigma(E)$ is the neutron scattering cross section for the gas in the counter. This relation assumes that the scattering is isotropic in center of mass coordinates, and that the range of the recoils corresponding to the bias energy B is small compared to the dimensions of the counter. Unfortunately the scattering cross section for argon is not known at present. Since the excitation curve for the Li^7 neutrons measured with the argon-filled counter very closely reproduces Richard's[13] results taken with a methane-filled electroscope, we may assume that there is no serious anomoly in the argon cross section over the wide range of energy of the Li^7 neutrons.

The neutron counting rate was measured as a function of deuteron energy over the energy range 200 kev to 2200 kev. The interval between successive points on the excitation curve is about one third the target thickness (375 micrograms/cm^2 Li_2SO_4, 128 kev for 1 mev deuterons), and each point represents a count of at least 1280 on the neutron counter. As had been expected, the excitation curve obtained in this way showed a slight rise in the neighborhood of the 1020 kev resonance in the excitation

curve for the neutrons produced by deuteron bombardment
of Li^7. To correct for this Li^7 impurity in the target,
it was necessary to repeat the experiment using a normal
Li_2SO_4 target which contains 7.5% Li^6 and 9.25% Li^7 [14].
The normal Li_2SO_4 target was 412 micrograms per sq. cm.
thick; all other experimental conditions were identical
with the Li^6 experiment. Knowing the relative amount of
each isotope in the two targets, and the yield for each
target, it is possible to calculate the contribution of each
isotope alone. The data, corrected to show the yield from
each isotope alone is plotted in Fig (10). The counting
rate units are arbitrary, but are the same for both curves.

7. NEUTRON EXCITATION CURVE DISCUSSION

The two curves in Fig (10) show that the yield of
neutrons from Li^7 is about twice the yield of neutron from
Li^6, except at the very lowest deuteron energies. Rumbaugh[15]
found more neutrons from Li^6 than from Li^7 below 1 mev, but
the difference in these results is likely due to the fact
that Rumbaugh's counter, a boron-lined ionization chamber,
is more sensitive to the lower energy neutrons from Li^6,
whereas in this experiment the lower energy neutrons were
biased out in the discriminator.

The excitation curve for the neutrons from Li^6 shows
no indication of sharp resonance peaks. Aside from the rise
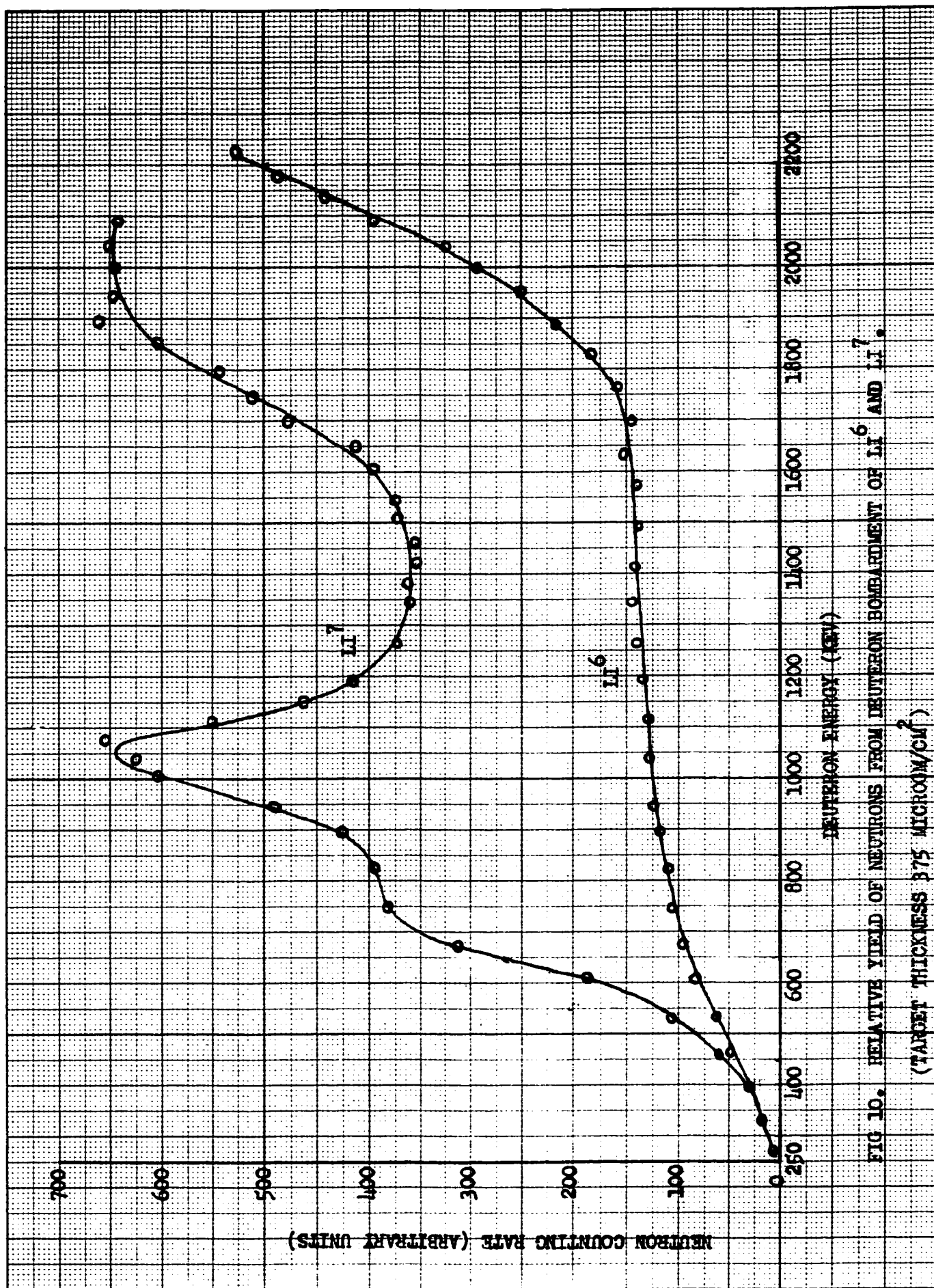above 1.8 mev, the shape of the curve is similar to the

FIG 10. RELATIVE YIELD OF NEUTRONS FROM DEUTERON BOMBARDMENT OF Li⁶ AND Li⁷.

(TARGET THICKNESS 375 MICROGM/CM²)

proton excitation curve. Interpretation of the Li^6 excitation data is difficult because of the uncertainty in the energies of the neutrons and consequently in the sensitivity of the counter. The rise above 1.8 mev may be due to a resonance level in Be^8 lying somewhere above the energy range of these measurements. The excitation curve above 1.8 mev can be fitted fairly well to an expression of the form of Eq. (2), using the values E_R ≈ 2.5 mev, Γ ≈ 0.8 mev, and the penetrability calculated for a p-deuteron. However, in view of the fact that the proton excitation curve does not show this rise, a more likely interpretation would seem to be that at deuteron energies above 1.8 mev, the energy of the neutrons from reaction[2] becomes greater than the bias energy, and, therefore, they are not counted at all at the lower deuteron energies. The possibility that this rise is due to neutrons from carbon contamination, or the S or O in the target, is excluded since the Li^7 excitation curve shows quite different behavior in this energy range.

The neutron excitation data was taken with a target that is too thick to make it worthwhile to look for the 365 kev resonance in the excitation function corrected for deuteron penetrability. It is difficult to estimate the loss of energy of a 350 kev deuteron in passing through a layer of Li_2SO_4 374 micrograms/cm^2 thick, because the stopping power of the target material varies considerably with deuteron energy in this low energy range; but the target thickness is probably on the order of 300 kev. Such a thick target will broaden out the resonance peak and displace it to a higher deuteron energy. In addition, because of the uncertain neutron energy, the correction to center of mass coordinates as uncertain. This correction must be applied to the data taken at 0° to account for variation in effective solid angle subtended by the counter at the target. The neutron excitation function in this region, about 350 kev, should be redetermined, using a thin target and observing the neutrons emitted at 90° to the deuteron beam.

8. NEUTRON ANGULAR DISTRIBUTION

To determine how accurately this neutron excitation curve taken at 0° to the deuteron beam represents the variation in the total cross section (for emission of particles into the whole solid angle), it is necessary to find out how the angular distribution of the neutrons varies

with bombarding energy. The counter used in the angular
distribution measurements is shown in Fig (11). It is an
argon filled proportional counter which contains 21 thin
foils of a hydrogenous material from which the incident
neutrons can knock recoil protons which will then be
counted. This counter was chosen because of its good
efficiency for high energy neutrons, and because its small
cross section (8.2 cm^2 with the counter aimed at the target
as shown) made it possible to place the counter conveniently
close to the target and still subtend a small solid angle
at the target, a necessary condition for good angular reso-
lution. The relatively high efficiency of this counter is a
result of the large quantity of hydrogen in the foils. Each
foil contains 30 mg/in^2 of Polythene, a polymer of ethylene
C_2H_4, and the 21 foils together present as much hydrogen
to an incoming neutron as if the counter were filled with
hydrogen at 15 atmospheres pressure. The associated
electronic equipment used with this counter is the same as
that described in connection with the argon counter. The
discriminator bias was chosen to make the counter insensi-
tive to gamma rays and the low energy neutrons from the
carbon contamination. The counter was mounted on a turn-
table, centered at the target, so that the counter could
move about the target at any angle from 0° to 150°. The
counter subtended a solid angle 0.025 at the target.

EXPERIMENTAL ARRANGEMENT USED IN TAKING NEUTRON
ANGULAR DISTRIBUTION DATA

KOVAR SEAL

PLOYTHENE FOILS
1/8 IN. HOLE IN CENTER

BRASS SPACER RINGS

TUNGSTEN WIRE
1 MIL.

GLASS SUPPORT

18°

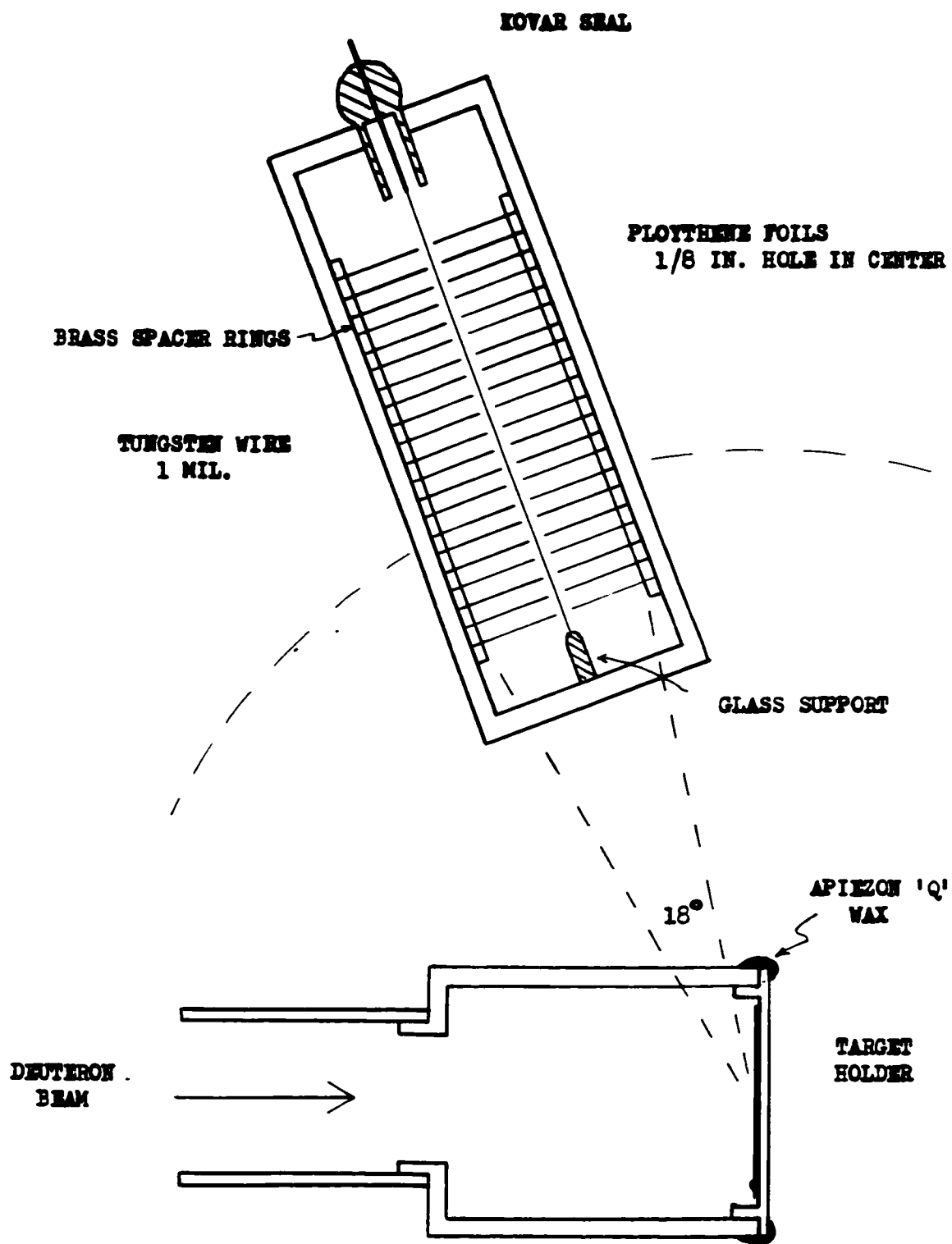APIEZON 'Q'
WAX

DEUTERON
BEAM

TARGET
HOLDER

FIG. 11

A rather serious disadvantage of this polyfoil
counter was that its efficiency was not constant from day
to day. The changes in efficiency were apparently slow
and uniform; but over a period of eight hours it would
drop sometimes by as much as 25%. To allow for this effect,
the following procedure was adopted. A given number of
neutron counts was taken first at 0°, then at 15°, 30°, etc.,
on around to 150°; then the measurements were repeated
starting at 150° and working back to 0°. If the difference
between the two measurements at same angle showed a uniform
increase from 150° to 0°, the data was accepted as good,
and the average of the two readings at each angle was taken
as the angular distribution. Using the same 375 microgm/cm^2
target used in taking the excitation data, the angular
distribution of the neutrons was taken at 600, 1000, and
1400 kev. The results are shown in Fig (12), the neutron
counting rate in arbitrary units is plotted as a function of
the laboratory angle of observation. Each point on the
600 kev curve represent a count of at least 640 neutrons;
on the other two curves, each point corresponds to a count
of 2560 neutrons.

The neutron angular distribution is primarily forward,
and the asymmetry increases with bombarding energy. This
means that our excitation curve taken at 0° will rise some-
what more rapidly with bombarding energy than the total cross
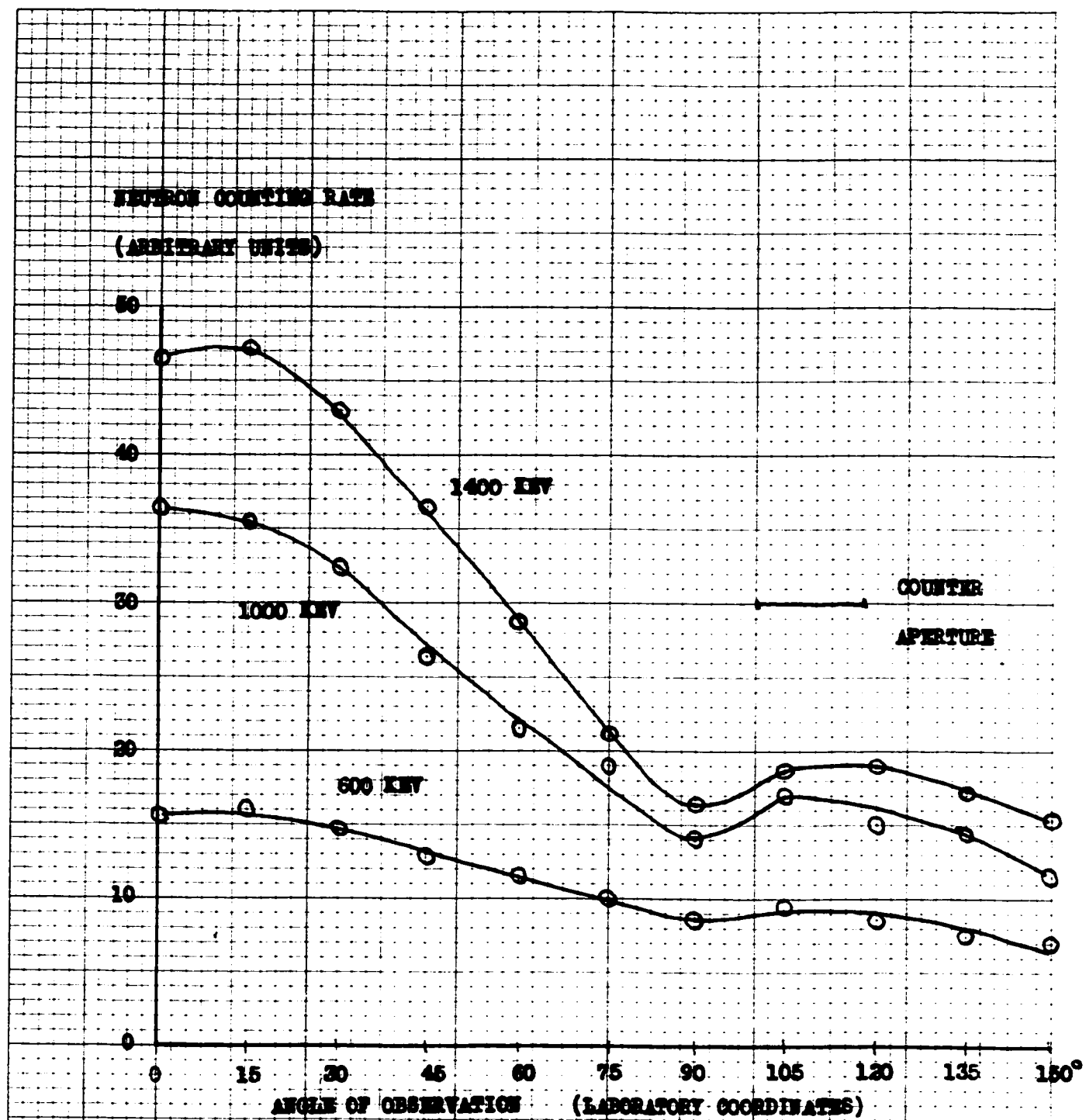section for emission into the whole solid angle. However,

FIG 12. ANGULAR DISTRIBUTION OF THE NEUTRONS FROM LI[6].

there are no radical changes in the distribution, so that
the total cross section will have the general shape as the
0° curve.

Since the energy of the neutrons is not homogeneous,
it is not possible to correct the angular distribution to
center of mass coordinates. These distributions in labora-
tory are similar to the proton distributions in laboratory
coordinates, differing in that the forward asymmetry is more
pronounced for the neutrons. If the neutron and proton dis-
tributions were actually the same in center of mass coordi-
nates, the neutron distribution would show greater forward
asymmetry in laboratory coordinates, since the lower Q value
for the neutron reactions makes the effect of the forward
motion of the center of mass more pronounced. Thus the
experimental results indicate that the angular distributions
of the protons and neutrons are not essentially different.

The angular distribution of the neutrons from Li^7
was also determined with the same experimental arrangement
at five bombarding energies, on the top and at either side
of the two peaks in the excitation curve. For this work
a thinner target was used, 106 micrograms per sq. cm. of
normal Li_2SO_4; the peaks in the excitation curve are then
more sharply defined. The distributions in laboratory angle
are shown in Fig (13).

In both the Li^6 and Li^7 neutron distributions,
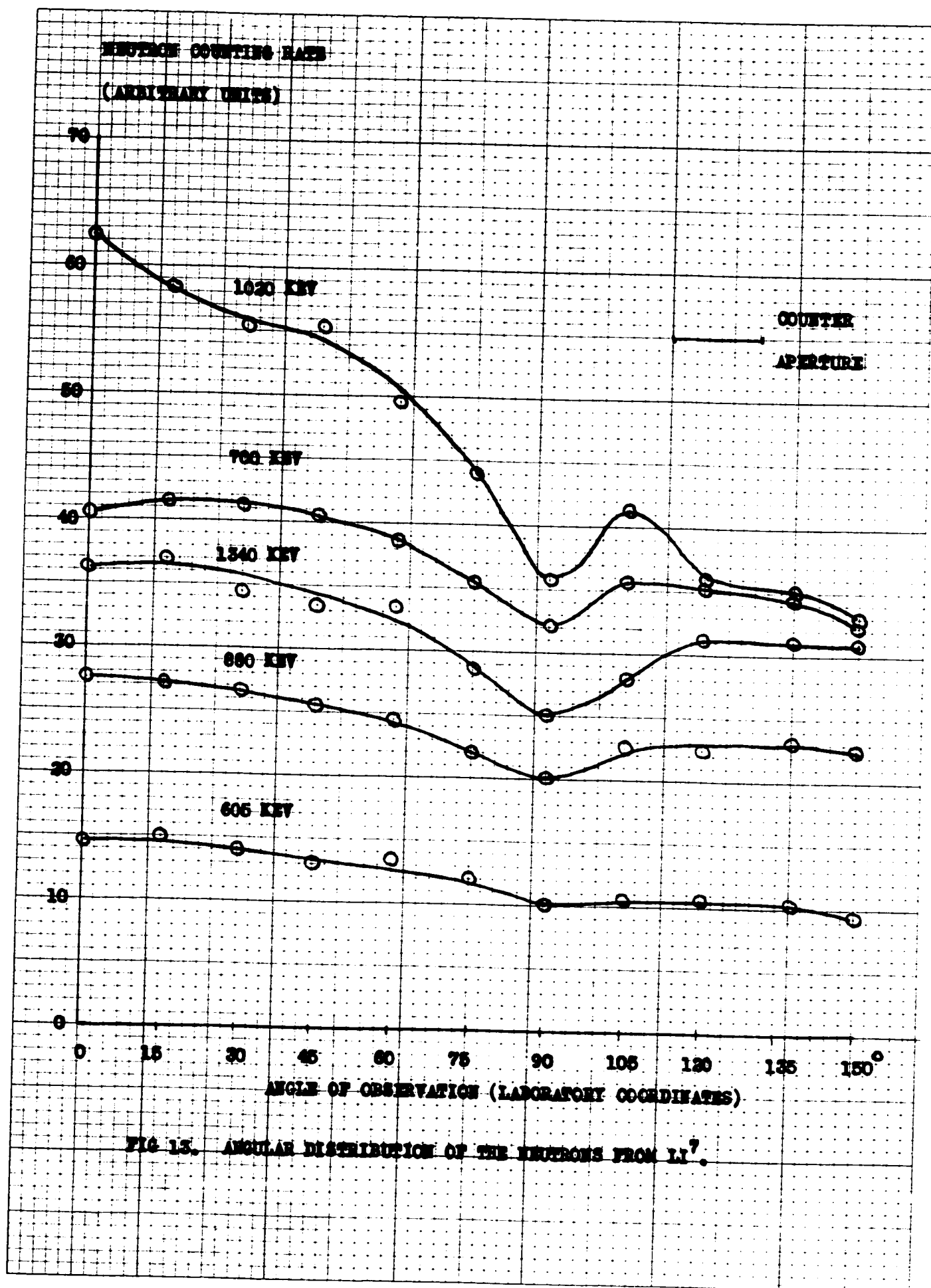there are pronounced dips at 90°. These are believed to be

FIG. 13. ANGULAR DISTRIBUTION OF THE NEUTRONS FROM Li^7.

spurious. As shown in Fig (11), the metal cap over the end of the glass vacuum tube is fastened vacuum-tight to the glass tube with Apiezon 'Q' wax, which contains hydrocarbons. With the counter in the 90° position, this wax is directly between the counter and the target, and it seems likely that neutrons emitted at 90° would be scattered away from the counter. Aside from these dips at 90°, the distributions, even in laboratory angle, are nearly spherically symmetric, except at the 1020 kev resonance. Correction to center of mass angle will lower the curve for angles less than 90° and raise it for angles greater than 90°; but these corrections will be small for the high energy neutrons from Li^7, those to which this counter is probably most sensitive. These results indicate that the distribution of Li^7 neutrons is very likely spherically symmetric, except at the 1020 kev resonance.

The forward asymmetry at the 1020 kev resonance is surprising. For an isolated resonance, the angular distribution of emitted particles must be symmetric about the 90° plane. Asymmetry about this plane is a result of interference between overlapping levels. For those excitation curves where a resonance peak is superimposed on a background due to broad overlapping levels, as it is in this case, Inglis[3] has pointed out that the angular distribution at the resonance should be more nearly symmetric about the 90° plane than the distributions on either side of the peak.

For this 1020 kev resonance just the opposite is true.
This raises some doubt as to whether this peak in the
excitation curve actually corresponds to the formation of
an excited state in Be^9 at this bombarding voltage. The
integrated yield of neutrons over the total solid angle
does show a rise here, on the basis of these five distri-
butions, but a more careful study of this resonance would
be desirable, although the presence of at least five dif-
ferent groups of neutrons makes the problem difficult.

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